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CHARACTERIZATION OF COLD MIXED ASPHALT EMULSION TREATED BASES

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PURDUE UNIVERSITY
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Final Report

CHARACTERIZATION OF COLD MIXED ASPHALT EMULSION TREATED BASES

TO: H. L. Michael, Director
Joint Highway Research Project

Project: C-36-45M

FROM: L. E. Wood, Research Engineer
Joint Highway Research Project

File: 6-18-12

The attached Final Report entitled "Characterization of Cold Mixed Asphalt Emulsion Treated Bases" is submitted for the JHRP Research Study of the same title. The author is Mr. Michel Mamlouk under the direction of Professor L. E. Wood of our staff.

The results of this study serve several purposes. It provides the highway engineer with a better understanding of the effect of different factors such as aggregate type and gradation, temperature, asphalt-emulsion content, curing, initial added moisture content and water sensitivity on the tensile and resilient characteristics as well as the different Hveem parameters of the asphalt emulsion mixtures.

Respectfully submitted,

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Final Report

CHARACTERIZATION OF COLD MIXED ASPHALT EMULSION TREATED BASES

by

Michel S. Mamlouk

Joint Highway Research Project

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Appendix A

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A.1 Components of the Asphalt Emulsion Mixture Specimen 176

LIST OF SYMBOLS

AE - Asphalt emulsion

AEM - Asphalt emulsion mixture

%AE Residue - Percent asphalt emulsion residue content*

%W - Percent initial added moisture content*

σ_{IT} - Indirect tensile strength

E_{IT} - Indirect tensile stiffness

M_R - Instantaneous resilient modulus

R - Hveem resistance R-value

S - Modified Hveem stability S-value

CM - Bulk specific gravity of the specimen after compaction

H - Specimen height, mm

G_d - Dry bulk specific gravity of the specimen

G_w - Wet bulk specific gravity of the specimen

γ_d - Dry unit weight of the specimen

γ_w - Wet unit weight of the specimen at time of testing

%WC - Percent of moisture retained at time of testing*

%TL - Percent of total liquid at time of testing*

%MA - Percent of moisture absorption during vacuum saturation*

$\%V_A$ - Percent of air voids at time of testing**

$\%V_W$ - Percent of voids filled with moisture at time of testing**

$\%V_T$ - Percent of total voids at time of test** = $\%V_A + \%V_W$

$\%VM_A$ - Percent of voids in mineral aggregate at time of testing**

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*Percent by weight of the dry aggregate.

**Percent by total volume of the specimen.

ABSTRACT

A detailed laboratory investigation was performed to characterize the performance of cold mixed asphalt emulsion treated bases for different mix components and environmental conditions. One asphalt emulsion (ISHC Designation AE-150), two aggregate types and gradations, two asphalt emulsion contents and three initial added moisture contents were evaluated. Three curing conditions and different test temperatures were used in the asphalt emulsion mixture evaluation.

Marshall size specimens were fabricated and evaluated using different tests. These were the indirect tensile test, resilient modulus test, and Hveem test. The effect of water on the mixture performance was investigated using the water sensitivity test. Correlations between the different asphalt emulsion mixture properties were examined. Subjective conclusions were established for the asphalt emulsion mixture performance for the various conditions.

The behavior of asphalt emulsion mixtures was highly influenced by test temperature. The effect of temperature was apparent on the tensile and resilient characteristics of the mixture. In addition, aggregate type, aggregate gradation, asphalt emulsion content and initial added moisture content proved to have an effect on the mixture performance. Curing was found to alter the asphalt emulsion mixture strength.

Asphalt emulsion mixture performance was somewhat affected by vacuum saturation. This effect was related to the amount of moisture absorbed into the mixture during saturation.

The indirect tensile test was easier to perform than the resilient modulus test. Also, the indirect tensile test provided consistant results compared to the resilient modulus test. In addition, the Hveem test was found to be suitable for the evaluation of asphalt emulsion mixtures at room temperature. Reasonable correlations were found between results of the indirect tensile test, resilient modulus test and Hveem test.

The results of this study serve several purposes. It provides the highway engineer with a better understanding of the effect of different factors on the tensile and resilient characteristics as well as the different properties of the asphalt emulsion mixtures.

CHAPTER 1

INTRODUCTION

Asphalt treated bases have many advantages over the untreated bases. As shown by many studies, asphalt helps in upgrading the low quality aggregates in such a way that locally available or on-site materials can be utilized. Also, asphalt provides cohesion to aggregates which has an effect on reducing the required structural section of the base course. Segregation and blowing dust are also minimized during construction. Moreover, asphalt treated bases can provide a temporary surface sufficient to carry present traffic till the funds for the final surfacing becomes available.

Asphalt emulsion mixture (AEM), on the other hand, has several potential advantages over hot mix asphalt cement. Unlike asphalt cement, emulsified asphalt when mixed with aggregate reduces or eliminates heating requirements. This has a significant effect on reducing energy demand and air pollution. In addition, either road mix or plant mix can be used for emulsified asphalt mix preparation. However, in spite of these advantages, the most critical shortcoming of asphalt emulsion treated materials is the relatively low strength at early ages and the long curing time required to develop the strength. The reason for this phenomenon is that the asphalt emulsion is a mixture of fine asphalt droplets dispersed in water. The binding effect of the asphalt residue is obtained when the water phase of the emulsion is evaporated and the asphalt residue forms a continuous film, coating the aggregate. Until

this evaporation occurs, there will be no adhesion between the asphalt and the aggregate surface. Therefore, the strength development of the asphalt emulsion mixes is limited by the rate of water loss in the mixture. This delay in strength development may require some compensation by increasing the required thickness of the base course than that required for hot mixes. In addition, the possibility of erosion and drop in mixture strength due to the presence of water in the system before complete curing can be important (53).

There are two main types of asphalt emulsion: anionic in which the asphalt droplets are electro-negatively charged and cationic in which its asphalt droplets carry electro-positive charges. Some studies have reported that the cationic emulsion type has a better coating ability for more aggregate types than the anionic type (25,29). According to these studies, most of the aggregate types have negative surface charges which provide a strong electrochemical bond or ionic attraction with cationic emulsion type. However, both anionic and cationic asphalt emulsions have been used successfully for may years (18). Although surface charge is important, each aggregate/emulsion mix has its own characteristics that must be determined through actual testing. Therefore, many recent research efforts do not direct any attention toward determining surface charges of the aggregates (25).

Based on the mix design methods available at the present time, the suitability of the asphalt emulsion for a particular type of aggregate is determined by the coating achieved after mixing and the resistance of the compacted mixture to moisture. Studies showed that coating is affected by several factors. These factors are aggregate/asphalt electro

surface charge, amount of moisture in the mix, mixing temperature and aggregate surface texture. In addition, the use of anionic high float asphalt emulsion in the asphalt emulsion mixes provides better coating than regular anionic types (18). The high float emulsion contains oil distillate which improves its coating ability. The base asphalt of the high float emulsion type is also modified during the emulsification process to be less temperature susceptible.

Asphalt emulsion treated bases have been used in both rigid and flexible pavements. Asphalt emulsion base projects show a very good performance throughout the United States. A case study was made to determine the performance of CRC pavements in Indiana (23). The study showed that the performance of asphalt treated bases beneath concrete pavements has, in general, been successful. However, in recent years, some distress has been noted on some of the heavy travelled roads having cold mixed asphalt emulsion treated bases. The reason for this distress could be the improper use of such asphalt emulsion treated bases, but this has not been determined with certainty.

A thorough understanding of the integral behavior of cold mixed asphalt emulsion treated base does not exist at present. Also, the resistance of the asphalt emulsion mixtures to moisture is questionable. The purpose of this study is to characterize the cold mixed asphalt emulsion mixtures used for black bases for the different mix components at different curing stages and environmental conditions. The different tests that have been used in this study to evaluate the performance of the asphalt emulsion mixes are as follows:

1. Indirect tensile test

2. Resilient modulus test

3. Water sensitivity test

4. Hveem stabilometer test

The relationships between the different test results have been investigated, and overall conclusions were derived.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Asphalt Emulsion Treated Bases

Asphalt emulsion mixture (AEM) has been used for base courses in a limited scale in the last few decades. The performance of the asphalt emulsion treated bases has been successful in most cases. However, a complete understanding of the behavior of the mixture for the different ingredients, curing stages and environmental conditions is still needed.

The asphalt emulsion mixture can be prepared by mixing the asphalt emulsion with damp aggregates, so there is no need for drying or heating. A certain amount of moisture is beneficial in distributing the asphalt films on the aggregate particles. A film of asphalt emulsion applied to a mineral aggregate will break to the original asphalt by both evaporation of the water and the electrochemical attraction of the charged asphalt particles to the aggregate (12). The compatibility between asphalt emulsion and aggregate is determined by the quality of coating and the water resistance of the compacted mixture.

At the present time, there is no mix design method for asphalt emulsion mixes that is recognized on a nationwide basis. There are, however, several mix design procedures currently used with varying degrees of success throughout the country. Among them are methods developed by the Asphalt Institute, Chevron, U. S. Forest Service, Armak, and FHWA Region 10 (Pacific Northwest) (25). In addition to these procedures, some researches in asphalt emulsion mixes have been per-

formed by Darter et al (18,19), Gadallah et al (27,28), Jimeniz (35), and George (29). Most of these mix design procedures are generally modifications of the Hveem or Marshall methods. Preparation and fabrication of specimens are similar in each method with differences existing primarily in the curing and testing schemes (25). These studies discussed the bonding mechanism between asphalt emulsion and aggregate particles. The effect of aggregate type, asphalt emulsion type, mixing water content, mixing time and asphalt emulsion content were also investigated. Some studies recommended criteria to be used in the design of asphalt emulsion mixes.

According to the previous investigations, it can be concluded that the behavior of the asphalt emulsion mixture is rather complex. Terral and Awad (56) reported that the asphalt mixture is a combination of non-linear elastic aggregate cemented by a non-linear viscoelastic asphalt. Therefore, the behavior of the mixture is neither elastic nore viscoelastic but rather non-linear combination of both. This behavior depends upon the mixture ingredients and the environmental conditions. In addition, the rate of curing is another factor to be considered in the asphalt emulsion mixture which makes its behavior more complicated.

The response of the asphalt emulsion mixes is time dependent as well as temperature dependent. Several tests are currently used to characterize the asphalt emulsion mixtures. The choice of these tests should take into consideration the behavior of the mixture as well as the usefulness, simplicity and the applicability of these tests. The tests that were considered in this study are the indirect tensile test, the resilient modulus test and Hveem test. Furthermore, the water sen-

sitivity test was used to evaluate the resistance of the asphalt emulsion mixture to water.

2.2 Indirect Tensile Test

The indirect tensile test was developed in 1953 by Carniero and Barcellus in Brazil (11) and independently by Akazawa in Japan (1). In this test, cylindrical specimens are failed by applying compressive loads along a diametrical plane through two opposite loading heads. This type of loading produces a relatively uniform tensile stress acting perpendicular to the applied load plane. Using photoelastic analyses of plastic disks a simplified mathematical treatment was given by Frocht (26). Timoshenko and Goodier developed the theory showing the stress distribution in a circular disk when two equal and opposite point loadings act along the diametrical plane (61).

According to Maupin (42) the advantages of the indirect tensile test are:

1. It is simple.
2. Marshall specimen may be used.
3. Surface irregularities do not seriously affect the results.
4. The coefficient of variation of the test results is low.

Several investigations have been conducted on asphaltic concrete specimens using the indirect tensile test. A long-term study was performed by the University of Texas at Austin to evaluate the tensile properties of highway pavement materials through the use of the indirect tensile test. Kennedy and others (30,31,37) reviewed and evaluated the techniques and procedures for obtaining fundamental properties of asphaltic concrete such as modulus of elasticity (stiffness), Poisson's

ratio, tensile strength and tensile strain. In these studies, factors having an influences on the tensile properties of asphalt treated materials were evaluated. Additional studies conducted at the University of Texas at Austin investigated the properties of Portland cement and lime treated asphaltic materials.

Tensile strengths of bituminous concrete at low temperatures were evaluated using the indirect tensile test (8). correlations between the indirect tensile stiffness and fatigue life were developed by Maupin (42). His study developed the concept of using the indirect tensile test to design asphalt concrete so that the necessary flexibility required to withstand repeated strain applications would be present. In another study by Ruth and Potts (47), laboratory specimens and cores were tested using the indirect tensile test. Relationships between energy and vertical and horizontal deformations were developed from the test data.

2.3 Resilient Modulus Test

When traffic moves over a pavement structure, a large number of stress pulses are rapidly applied to the different pavement layers. The concept of repeated load tests was developed to approximate the dynamic loading conditions that actually occur beneath the pavement surface. One of the common repeated load tests is the resilient modulus test. Briefly, pulse loads are applied to asphaltic concrete specimens and the corresponding recoverable strains are measured. The resilient modulus (M_R) is defined as the ratio of the applied stress to the recoverable strain when a dynamic load is applied. It is used as one of the inputs of the multilayer elastic and the finite element design methods of the

highway pavement (9,46). The resilient modulus for the asphalt concrete can be determined in the laboratory by using several different modes of repeated loads. Among these modes are the triaxial compression test, the flexural beam test, the direct tension test and the diametral compression test. The first three tests requires large specimens and long and rather difficult procedures, especially the triaxial compression test. The diametral compression test is preferred over the other tests because it is simple, rapid and required Marshall size specimens.

The diametral compression test procedure to determine the resilient modulus of asphaltic concrete was developed by Schmidt (51). According to this method, a pulsating load is applied across the vertical diameter of Marshall specimens every 3 seconds with a 0.1 second duration and the corresponding horizontal deformation is recorded. The M_R value was calculated assuming Poisson's ratio of 0.35 at ambient temperatures. Comparisons of M_R values using direct tension, compression, flexural and diametral methods were investigated (51).

Schmidt et al (53) determined the resilient modulus (M_R) of an SS-type asphalt emulsion mix. It was found that the M_R values varied directly as the hardness of the asphalt used to make the emulsion. Air-cured emulsion treated mixes attained M_R values higher than the M_R values of hot mixes made with the same asphalt. However, water resistance of emulsion treated mixes was lower than asphalt treated mixes until the emulsion treated mixes were fully cured. Schmidt and Graf (50) studied the effect of water on the resilient modulus of asphalt treated mixes.

Further work was performed to determine the effect of temperature, freeze-thaw, and various moisture conditions on the resilient modulus of several asphaltic mixtures. It was found that the emulsion treated mixtures were less temperature susceptible than hot mixed asphaltic concrete made with the same asphalts and aggregates (52). The performance characteristics of cement - modified asphalt emulsion mixes were studied using the resilient modulus test (53). The same technique was used to characterize different asphaltic concrete mixtures and recycled asphalt concrete (17,22,38). A tentative recommended procedure was developed that correlates the resilient modulus of the cold mixed base (using Schmidt procedure) with the structural coefficient of the base course as used in the AASHTO Interim Guide for design of flexible pavements. The amount of permanent deformation of cold asphaltic mixtures under repeated loads is believed to be highly related to the M_R value of the mixture (17).

One of the criticisms using Schmidt's technique is the assumption of Poisson's ratio. A 40 percent change in the computed value of M_R can result when Poisson's ratio varies from 0.25 to 0.45. Therefore, the experimental determination of Poisson's ratio is preferred. The studies performed at the University of Texas at Austin determined Poisson's ratio experimentally by measuring the vertical deformation of the specimen as well as the horizontal deformation (37). In these studies, the MTS electro-hydraulic system was used. A haversine compressive load was applied to asphaltic concrete specimens for 0.4 sec and removed for 0.6 sec at a frequency of one cycle per second. Using the same technique, fatigue results were compared with results from other commonly used

tests such as the creap test. Fatigue behavior and the effect of repeated tensile stresses on the resilient characteristics of asphaltic mixtures were evaluated using the repeated-load indirect tensile test (37).

2.4 Water Sensitivity Test

For proper Asphalt Emulsion Mix characterization, tests should be performed under conditions that simulate or reflect the actual conditions present in the pavement structure. One of the conditions that should be considered in the mixture characterization is the presence of water. Because of the relatively low permeability of asphalt treated material, the water may be trapped in the mixture producing a substantial decrease in its stiffness. This can be attributed to the stripping action and loss of adhesion between asphalt and aggregate particles. The asphalt mixture which is least affected by the presence of water would be best suited for pavement.

Several studies have investigated the effect of water on the different types of bituminous mixtures. Lottman et al (39) developed a laboratory test system to predict moisture damage in asphaltic concrete pavements. Moisture damage predictions were based on the results of tensile strength and tensile E-moduli tests performed on specimens that have undergone freeze-soak and thermal-cycle accelerated moisture conditions. Schmidt and Graf (50) determined the effect of long-term vacuum saturation on the resilient moduli of asphaltic concrete specimens at different temperatures. In general, a reduction in the resilient modulus value was found due to vacuum saturation. At high asphalt content levels, however, the effect of water saturation was eliminated com-

pletely. The decrease in the resilient modulus was proportional to the concentration of water present in the specimens. It was found also that the resilient moduli of moisture deteriorated specimens return to their original values upon drying. The effect of vacuum saturation on cement-modified asphalt emulsion mixes was studied by Schmidt et al (53). Other methods are currently being used to test the effect of moisture on bituminous treated materials such as swell test and other vacuum soaking procedure (40).

In this study, a modification of the Asphalt Institute method was used to determine the effect of water on the performance of Asphalt Emulsion Mixes (5). It was found that this test was suitable for these kinds of mixtures (27). According to this method, specimens are vacuum saturated and soaked for one day before being tested. A comparison was made between dry specimens and vacuum saturated specimens.

2.5 Hveem Test

The Hveem stability design method has been developed by the California Division of Highways and standerdized by ASTM Designation D 1560 (AASHTO Designation T246). This method is used in the design of dense graded hot asphalt paving mixtures. It is currently used in Indiana for both laboratory design and field control of hot mixed asphalt pavement (33). In this method, the Hveem stability (S-value) is determined using the Hveem stabilometer. The same equipment has been used also to determine the Hveem resistance (R-value). This test is commonly used in the west coast for the evaluation of stabilized base mixtures (13). The test has been standarized by ASTM Designation D2844 (AASHTO Designation T190). The temperature for the standard Hveem stability test is 60^{o}C

(140°F), while for the Hveem resistance test is 22 ± 3°C (72 ± 5°F). Some studies, however, determined both R and S values for asphalt mixtures at ambient temperatures. Also, both R and S values were determined for the same specimen (35, 60).

Hveem R and S values are generally used for laboratory mix design as well as field control. They can be used also for the characterization of bituminous mixtures. The purpose of using the Hveem test in this study was to characterize the Asphalt Emulsion Mixes by using both R and S values at ambient temperatures. Correlation analyses were tried between the Hveem test, the indirect tensile test and the resilient modulus test results.

CHAPTER 3

MATERIALS AND SPECIMEN PREPARATION

3.1 Mineral Aggregate

Two types of mineral aggregate were used in this study. The first type was a mixture of sand and gravel. The second type was a crushed limestone. The two aggregate types have been used in earlier studies (27,49). The characteristics of these aggregates will be discussed in the following paragraphs.

The sand and gravel mixture was obtained from the Western Material Company, a division of Medina Aggregate Company in West Lafayette, Indiana. The plant is listed as source No. 2132 by the Indiana State Highway Commission (ISHC). This aggregate is a terrace sand and gravel material deposited by the early Wabash River. It consists of approximately two-thirds weathered limestone and dolomite aggregate and one-third non-carbonate aggregate. Small amounts of granite and quartzite were present in the sample. 56% of the gravel particles retained on No. 4 sieve had crushed faces while 28% of the crushed particles are mechanically crushed.

The crushed limestone was provided by the Erie Stone Company in Huntington, Indiana. The quarry is listed as source No. 58 by the ISHC and source No. 35-1 by the Geologic Survey. The material is a fossiliferious, recrystallized limestone with some sandstone and shale inclusions. Other properties of both aggregate types which were used in the study are shown in Table 3.1.

Table 3.1, Aggregate Properties

	Sand and Gravel	Limestone
Apparent Specific Gravity	2.707	2.741
Bulk Specific Gravity (SSD)	2.607	2.696
Absorption, %	1.20	1.28

The aggregate was dried and separated into the different sieve sizes. The different aggregate sizes were batched in 1200 gram batches according to the required gradations. Two aggregate gradations were used in the study with a maximum size of 19mm (3/4 in.) as shown in Figure 3.1. The first was a medium gradation (MG) which followed the mid specification of the ISHC #73B gradation band. The second was coarse gradation (CG) which was selected at the "quarter point"; midway between the midpoint and the lower limit of the specification band.

3.2 Asphalt Emulsion

ISHC designation AE-150 mixing grade emulsified asphalt was used in this study. It was formulated and provided by the K.E. McConnaughay Laboratory in Lafayette, Indiana. The properties of the asphalt emulsion are as follows:

Saybolt Fural viscosity, sec.	50+
Residue by distillation, %	70.0
Penetration of residue after distillation, 25°C (77°F), 5 sec., 100 gm	200+
Specific gravity of residue after distillation, 25°C (77°F)	1.010

This is a high float anionic type of asphalt emulsion and is similar to HFMS-2S (ASTM Designation D977).

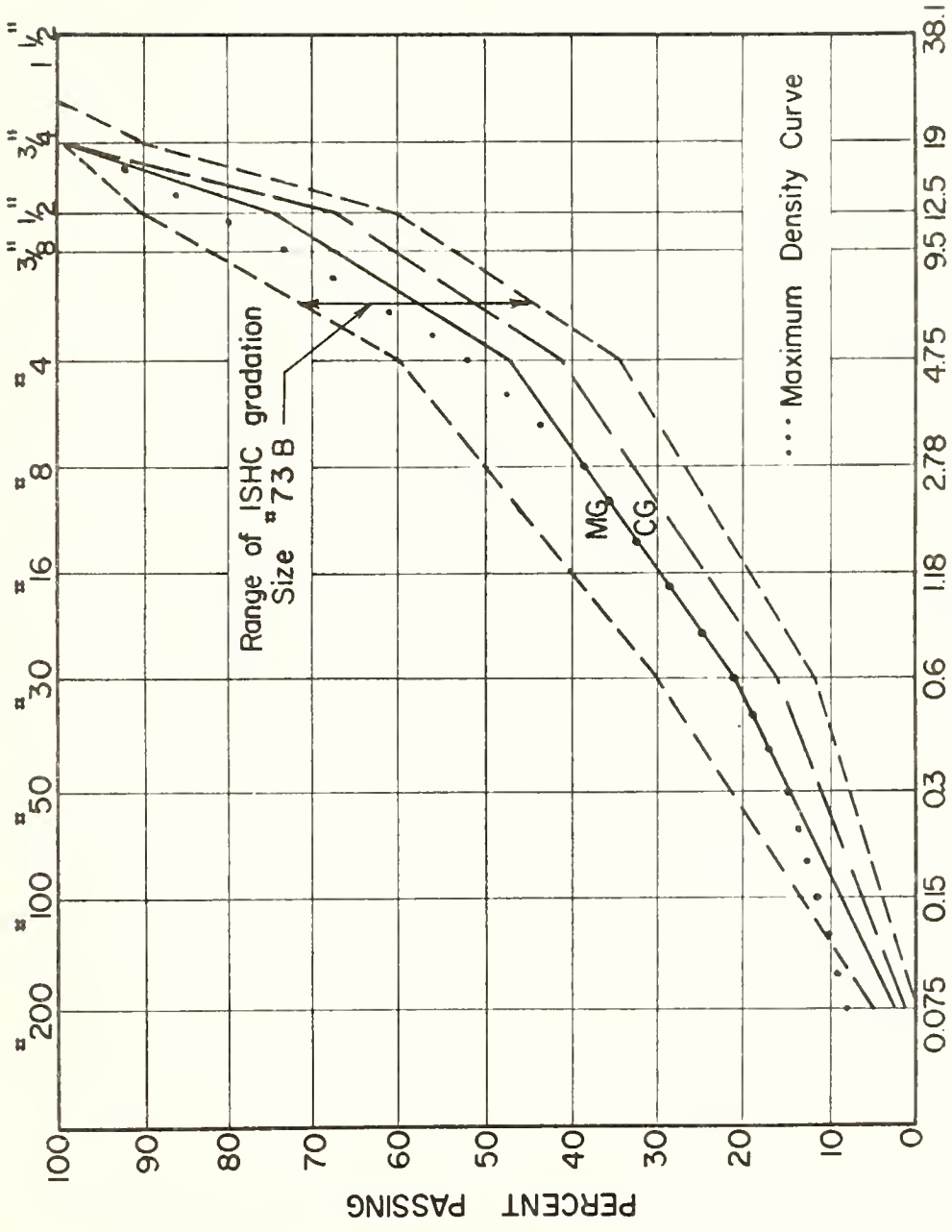


FIGURE 3.1, AGGREGATE GRADATION

3.3 Compaction

Specimens were compacted in a fixed roller gyratory compaction machine (Figure 3.2). The gyratory machine was used because it produced consistant samples that resembled actual conditions in the field. In accordance with one of the standard gyratory compaction methods, the gyratory angle was set at 1 degree and the ram pressure was set at 1.38 MPa (200 psi).

A preliminary investigation was conducted in which the number of revolutions was varied and the bulk specific gravity of the specimens were determined. It was determined that 20 revolutions of the gyratory machine would produce specimens having approximately the same bulk specific gravity as specimens obtained by applying 50 blows of the Marshall hammer on each side. The compacted specimens would simulate pavement material under medium traffic compaction in the field. Therefore, a compaction effort of 20 revolutions at 1.38 MPa (200 psi) was used to compact all specimens tested in this study. No heating was provided by the gyratory machine during compaction. The mold and the mold chuck were operated at a room temperature of approximately 22°C (72°F). The Asphalt Emulsion Mixes were heated before compaction as will be discussed later in this chapter.

The gyrograph was used to indicate the stability of the mixture during compaction. A typical gyrograph band may be seen in Figure 3.3. It was noted that the gyrograph band showed constant gyration angle throughout the compaction process in almost all cases. This indicates that the asphalt emulsion mixture used in the study was quite stable. It should be pointed out, however, that using this kind of compaction

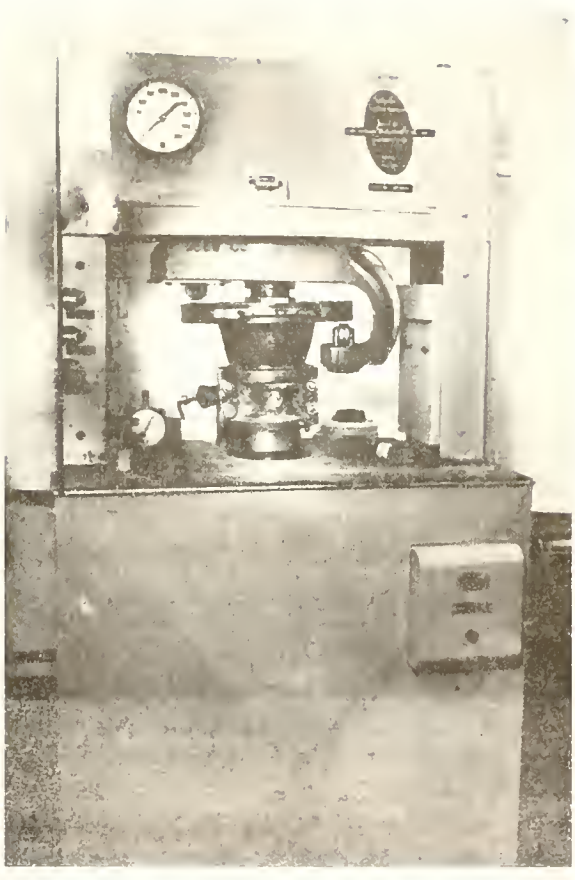


FIGURE 3.2 , GYRATORY COMPACTION MACHINE

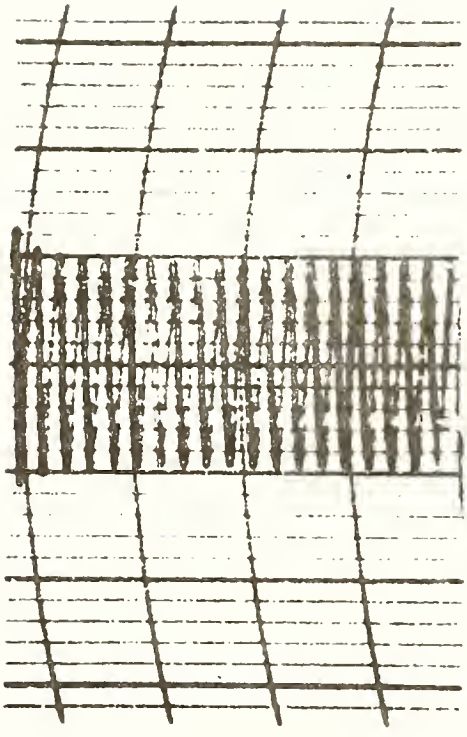


FIGURE 3.3, TYPICAL GYROGRAPH BAND DURING COMPACTION OF ASPHALT EMULSION MIXTURES

for mixtures containing 4.5% initial mixing water and 4% asphalt residue caused some excess water together with some fines to be forced out of the mold during compaction. This indicates that 4.5% initial mixing water would be more than the optimum amount required for this type of mixture, especially when using this method of specimen preparation procedure, and when the asphalt residue content is as high as 4%.

3.4 Mix Design and Specimen Preparation

Unlike the traditional hot mix asphaltic concrete, the performance of asphalt emulsion treated mixtures is affected by many factors during mixing and preparation. As a result, more effort is needed in controlling and handling the Asphalt Emulsion Mixes in order to obtain a good performance. The review of the literature shows that some studies have been performed to establish a procedure for cold mixed Asphalt emulsion Mixtures. However, no single method has been adopted as a standard method. The basic design procedures using dense graded aggregates consist of the following steps (25):

1. Determine the suitability of the aggregate.
2. Establish a beginning emulsion content for trial mixtures.
3. Determine the amount of water necessary during mixing to produce the desired coating and workability using a given type and grade of emulsion.
4. Determine the optimum moisture content needed for compaction.
5. Fabricate specimens using different emulsion contents and subject them to various curing and soaking conditions.
6. Test the specimens for stability and strength.
7. Select the specimen that best meets the design requirements and

recommend a job mix formula.

In this study, specimens were prepared according to the method of design developed by Gadallah (27) except for the compaction type. Both aggregate and asphalt emulsion were checked to meet the requirements of ISHC standard specifications. The compatibility of aggregate and asphalt emulsion was evaluated based on the coating test (33). A range of acceptable amounts of mixing water was recommended taking into consideration the aggregate coating, workability of the mix and the curing rate of the specimens before and after compaction. A range of asphalt emulsion content was used which is recommended by ISHC standard specifications.

The main pieces of equipment used in the preparation of specimens were: ovens, a mechanical mixer, and the gyratory machine. Two forced draft ovens were used in the mix preparation. The oven which was frequently used had a capacity of 0.5 cubic meter (18 cubic foot), while the other one had a capacity of 0.028 cubic meter (1 cubic foot). The mixing was accomplished using a type N-50 Hobart rotary mixer with whip attachments.

Marshall size specimens with a diameter of 102 mm (4 in.) and about 64 mm (2.5 in.) in height were prepared. Procedures for specimen preparation were the same for all the specimens used in the different sections of the study. The specimen preparation procedures are outlined below:

1. Batches of 1200 gm (2.64 lb) of the dry aggregate were weighed out according to the required gradation.
2. The minimum amount of mixing water required to darken the aggregate

was added at room temperature [22°C (72°F)] and mixed thoroughly with a spoon. In this study, values of 1.5, 3 and 4.5% mixing water by weight of dry aggregate were used.

3. The wet aggregate was left at room temperature for 10-15 minutes to allow the mixing water to fill the surface voids of aggregate and to obtain a uniform coating of moisture over the aggregate.
4. The amount of asphalt emulsion needed to provide the required asphalt residue content was added. Two levels of asphalt residue content were used which were 3.25 and 4% by weight of dry aggregate.
5. The blend was mixed using a mechanical mixer for about 1 1/2 minutes. This was followed by a 30 sec. hand mix using a spoon to avoid any segregation between the fine and coarse aggregates during the mechanical mixing. If segregation occurs, this hand mixing should be done in the middle of the mechanical mixing period.
6. The mixture was cured in a forced-draft oven for one hour at 60°C (140°F). This precompaction curing process was introduced to take into consideration the high energy provided in the field during the mixing operations. It was found that this curing process provided a better coating of aggregate and an easier mixture handling than the case of a complete cold process. In this case, a mixture temperature about 43°-49°C (110-120°F) was reached in the oven which is considered reasonable for cold and intermediate asphalt emulsion treated mixtures. This method of precompaction curing was selected after comparing and evaluating different methods of mixture handling before compaction (27).

In general, it was found that the asphalt emulsion formed a fairly good coating over the aggregate particles especially the limestone. The coating and the workability of the mixture were further improved by the one hour curing in the oven.

7. After curing the mixture for one hour in the oven, the mixture was mixed for 30 seconds using a mechanical mixer.
8. specimens were compacted in a fixed roller gyratory compaction machine as discussed before. Immediately after compaction, the specimen height was determined according to ASTM D3387 method. Specimen weights were determined while they were still in the mold to avoid any damage. Using the determined height and weight of the specimen, the unit weight after compaction was calculated.
9. Half an hour after compaction, the compacted specimens were extruded from the molds and left to cure. Specimens were cured at a room temperature of 22°C (72°F) for either one day or three days. Other specimens were cured for three days in a forced-draft oven at 49°C (120°F) as required by the experiment design. Oven cured specimens were left for about 4 hours to adjust to room temperature. After curing, the specimen's heights were determined using a caliper.

The wet unit weight of the specimen was determined according to ASTM method No. D1188 after some modifications. In this method, the specimen was weighed in air then coated with zinc stearate instead of paraffine (16). After coating the specimen with zinc stearate, the specimen was weighed in water. Zinc stearate, which is a light powder, kept the moisture content of the specimen constant while being immersed in water. A limited study was performed to check the effect of zinc

stearate on the moisture content of the specimen. It was found that the moisture content of the specimen did not increase more than 0.25% of the dry weight of aggregate during immersion in water especially when the specimen surface was smooth.

After the wet unit weight was determined, the specimens were put in sealed plastic bags and kept between 2-4 hours in the temperature required for the test. When the test was completed, specimens were broken appart and dried in a forced draft oven for 24 hours at 110°C (230°F) then weighed. The oven dried weight of the specimen, which is the weight of the dry aggregate and the asphalt residue, was used in calculating the dry unit weight and the amount of moisture retained at time of testing as shown in Appendix A.

3.5 Inspection of the Asphalt Emulsion Mixes before and after Compaction

During the preparation process of the Asphalt Emulsion Mix specimens used in this study, some observations were made concerning the compacted specimens. Among these observations; a very good coating of limestone particles with asphalt emulsion was achieved compared to gravel particles. Stripping was noted in some gravel particles because of mineralogical compositions as well as their smooth surfaces and round shapes. The difference in coating, surface roughness, and shape between limestone and gravel particles was reflected in the results of the different tests. The overall result was that limestone provided a stronger asphalt emulsion mixture then sand and gravel. It was also noted that the precompaction curing improved the coating and removed some of the excess water from the mixture. Some mixtures used in this study, howev-

er, included an excessive amount of water which was forced out of the mold during compaction as mentioned before. This occurred when the initial added moisture was 4.5% and the asphalt emulsion content was 4% by weight of the dry aggregate.

It was noted also that limestone compacted specimens had a smooth surface when compared to sand and gravel specimens. Therefore, limestone specimens were easier to extrude from the mold than sand and gravel specimens. Unlike limestone specimens, sand and gravel specimens were more fragile and occasionally some gravel particles would dislodge from the specimen surface especially when the asphalt emulsion content was low. In general, limestone compacted specimens were easier to handle then sand and gravel specimens.

CHAPTER 4

INDIRECT TENSILE TEST

4.1 Introduction

As the traffic load is applied to the highway pavement, the bottom surface of the base course is subjected to tensile radial and tangential stresses. It is very important to determine the tensile characteristics of the different pavement layers in order to achieve a good performance of the highway structure. One of the simple tests which is used frequently to evaluate the tensile properties of the pavement materials is the indirect tensile test. The test is conducted by applying a vertical load across the vertical diameter of the cylindrical specimen till failure and recording the vertical and horizontal deformations.

The theory of the test assumes an isotropic and homogeneous material with a linear elastic behavior. Materials such as steel or aluminum more closely approximate these assumptions than an asphalt mixture. However, it is thought that the random distribution of aggregate particles in asphalt mixture tends to minimize the effect of hetrogeneity (30). Also, at a fast rate of loading a bituminous mixture shows a reasonable elastic behavior. The theory also assumes plane stresses in the specimen. This assumption is not totally met in Marshall specimens but it gives close approximations. These discrepancies between the theory and the test application are not considered serious, and the advantages of the test seem to outweigh the disadvantages. Moreover, it is

currently considered that a linear elastic analysis provides adequate solutions for most rational design purposes.

The stress distribution using loading strips of width less than 0.1 x the specimen diameter is shown in Figure 4.1. The compressive stress along the vertical diameter is three times that of the tensile stress. In order for this test to be applied to a material, it must be at least three times stronger in compression than in tension. Since the asphalt treated mixtures can withstand considerable more compression stress than tensile stress, the specimen will fail in tension.

4.2 Design of Experiment

The purpose of this study was to evaluate the effect of some factors on the response properties of Asphalt Emulsion Mixes. The Analysis of Variance (ANOVA) statistical method was used to determine the significance of certain factors and interactions of factors. The means of the response variables in each factor combination (cell) were used in observing any physical trends that might be present. Finally, subjective conclusions on the performance of the Asphalt Emulsion Mixes were established. The response variables and the independent variables (factors) which were considered in this part of the study are presented in Sections 4.2.1 and 4.2.2.

4.2.1 Response Variables

The response variables were measured to evaluate the performance of the asphalt emulsion mixes for the different factors considered in the study. Some of the response variables were measured to give indications of the tensile properties of the asphalt emulsion mixtures, while others

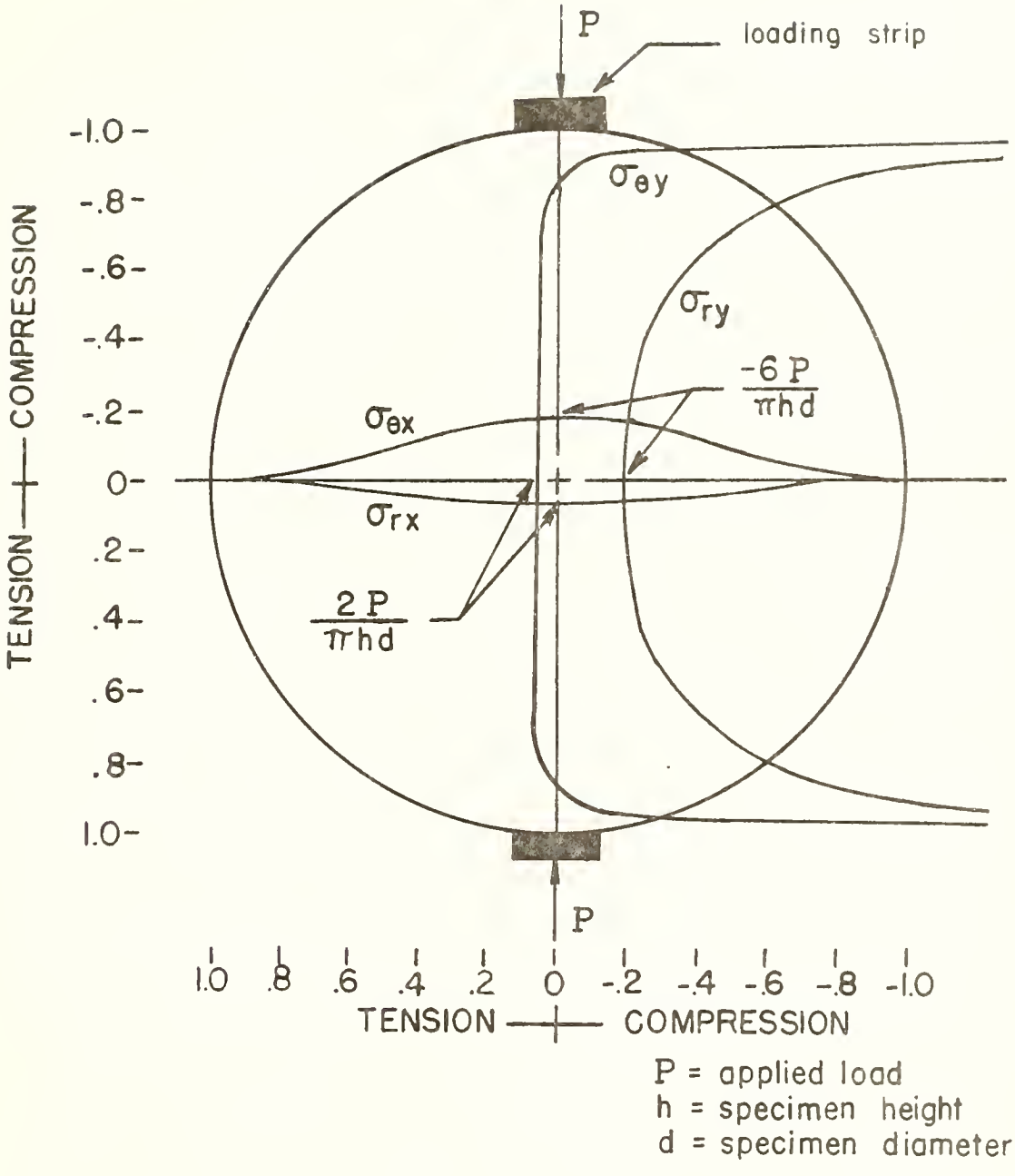


FIGURE 4.1, STRESS DISTRIBUTION ALONG THE PRINCIPAL AXES FOR LOADING STRIP WIDTH LESS THAN d/10

dealt with their physical characteristics. The response variables that were evaluated in the study were as follows:

1. Indirect tensile strength (σ_{IT}), as determined by obtaining the maximum load which the specimen could resist before failure (see Equation 4.1).
2. Poisson's ratio (ν), as determined from the ratio of the recorded vertical deformation vs. the horizontal deformation of the specimen during the loading operation (see Equation 4.2).
3. Indirect tensile stiffness (E_{IT}), as obtained from the continuous recording of the load vs. the horizontal deformation of the specimen during the load application (see Equation 4.3).
4. Total tensile strain at failure (ε_T), as determined using the total horizontal deformation at failure. Failure is defined to occur at the maximum load which the specimen can resist (see Equation 4.4).
5. Indirect tensile index, as represented by the slope of the line connecting the origin point to the point corresponding to 50% of the maximum load on the load vs. horizontal deformation curve (Figure 4.5). It is a measure of the relationship between the load increments and the resulting horizontal deformation. It is believed that this new parameter, in addition to other conventional design parameters, would provide a good characterization and design concept for the asphalt emulsion mixture.
6. The unit weight of the specimen immediately following compaction as a measure of compactability of the mixture. It was determined by obtaining the specimen weight and height just after compaction.

7. Wet and dry unit weights at time of testing. The wet unit weight refers to the density of the specimen after curing including the moisture portion. The dry unit weight was determined by excluding the moisture portion in the specimen.
8. Moisture retained in the specimen at time of testing (after curing), as a percent by weight of the dry aggregate.
9. Total liquid in the mixture at time of testing as a percent of the dry weight of aggregate; which is the sum of the percent asphalt emulsion residue and percent moisture retained after curing.
10. Voids at time of testing (after curing), which included:
    a. Air voids in the compacted asphalt emulsion mixture.
    b. Total voids; which are the sum of air voids and voids filled with moisture in the compacted mixture.
    c. Voids in the mineral aggregate, VMA; which are defined as the intergranular void spaces between the aggregate particles in the compacted asphalt emulsion mixture.

    Voids were expressed as percents by the total volume of the compacted specimen. They were calculated on the bases of the apparent specific gravity of the aggregate and assumed no asphalt was absorbed into the aggregate. Typical voids calculation are shown in Appendix A.

4.2.2 Independent Variables (Factors)

The study determined the influence of several factors on the performance of the AEM. These factors are as follows (Table 4.1):

1. Aggregate type, AG; two aggregate types were used in the indirect tensile test. The first type was a mixture of sand and gravel while

TABLE 4.1 , INDIRECT TENSILE TEST VARIABLES

Curing	Test Temp.	% Added Moisture	% AE Residue	Aggregate: Sand & Gravel 3.25	Sand & Gravel 4.00	Limestone 3.25	Limestone 4.00
1 – Day Air Curing	10 C (50F)	3		X	X	X	X
		4.5		X	X	X	X
	24 C (75F)	3		⊗	⊗	⊗	⊗
		4.5		X	X	X	X
	38C (100F)	3		X	X	X	X
		4.5		X	X	X	X
3 – Day Oven Curing	10 C (50F)	3		X	X	X	X
		4.5		X	X	X	X
	24C (75F)	3		⊗	⊗	⊗	⊗
		4.5		X	X	X	X
	38C (100F)	3		X	X	X	X
		4.5		X	X	X	X

Note:

Aggregate gradation : MG

X : dry test

○ : water sensitivity test

the second type was crushed limestone.

2. Asphalt emulsion residue content, AE. Two levels of asphalt emulsion residue contents were used; 3.25% and 4% of the dry weight of aggregate. These levels of asphalt residue content were chosen in accordance with ISHC standard specifications which call for a range of 2.5 to 4.5% by weight of the total mixture exclusive of water or solvent (33).
3. Initial added moisture, W; two levels were used which were 3 and 4.5% by weight of the dry aggregate. These two levels of added moistures fell within the range which provided reasonable coating of asphalt residue on the aggregate particles.
4. Curing, C; both one-day air curing at 22°C (72°F) and three-day oven curing at 49°C (120°F) were evaluated in the study. They represented the early curing condition (after construction) and the long-term curing condition in the field respectively.
5. Test temperature, T, three temperature levels were used in the indirect tensile test. These temperature levels were 10, 24, and 38°C (50, 75, and 100°F respectively).

One aggregate gradation was used in this phase of the study which followed the mid specification of the ISHC #73B gradation band (MG) with a top size of 19 mm (3/4 in.) (Figure 3.1). Three replicates for each combination were tested. The total number of specimens tested in this study were 144 representing all the different factor combinations mentioned above.

4.2.3 Statistical Model

The statistical Analysis of Variance tests used in this part of the study followed the following statistical model.

$$y_{ijk\ell} = \mu + R_i + \delta_{(i)} + M_j + RM_{ij} + \gamma_{(ij)}$$

$$+ C_k + RC_{ik} + MC_{jk} + RMC_{ijk} + \omega_{(ijk)}$$

$$+ T_\ell + \ldots + \varepsilon_{(ijk\ell)}$$

where

$y_{ijk\ell}$ = measured response variable (strength, stiffness ..)

μ = overall mean

R_i = effect of replicates

M_j = AG + AE + W + interactions

AG = effect of aggregate type

AE = effect of asphalt emulsion residue content

W = effect of initial added moisture content

C_k = effect of curing

T_ℓ = effect of test temperature

$\delta_{(i)}$, $\gamma_{(ij)}$ and $\omega_{(ijk)}$ = restrictions on randomization (2)

$\varepsilon_{(ijk\ell)}$ = experimental error

All main effects were fixed except R was random. The subscripts assumed values:

$i = 1,2,3$ $\quad j = 1,2$ $\quad k = 1,2$ $\quad \ell = 1,2,3$

This statistical model is a result of a split plot design (2). According to this model, one replicate (R) for all combinations was performed first. The second replicate was performed next then the third replicate. For every replicate, tests were performed on specimens having a certain curing level before considering the other curing levels. Also, for every curing level, specimens were tested at a certain temperature (T) before testing other specimens at another temperature. Tests were randomized for the different aggregate types (AG), asphalt emulsion contents (AE) and initial added moisture contents (W) within each combination of replicate, curing and test temperature levels.

All factors and interactions were tested versus their interactions with the replicate (R) (see Appendix B). This method of design allows analysis of variance (ANOVA) tests for all factors and interactions despite the restrictions on randomization. A level of significance of 5% was considered in the evaluations of the different factors.

In addition to the different factors mentioned above, a limited number of specimens were fabricated using the coarse aggregate gradation, CG (Figure 3.1) and tested with the indirect tensile test machine. The effect of aggregate gradation will be discussed in Section 4.4.11.

4.3 Equipment and Experimental Procedure

4.3.1 Equipment

The MTS electro-hydraulic closed loop testing machine was used in the indirect tensile test (Figure 4.2). The machine consisted mainly of a control unit, load frame, load cell, servovalve and hydraulic power supply. Two stainless steel loading strips 12.7 mm (1/2 in.) wide were used to apply the load to the specimen as shown in Figure 4.3. The

FIGURE 4.2, MTS ELECTRO-HYDRAULIC MACHINE

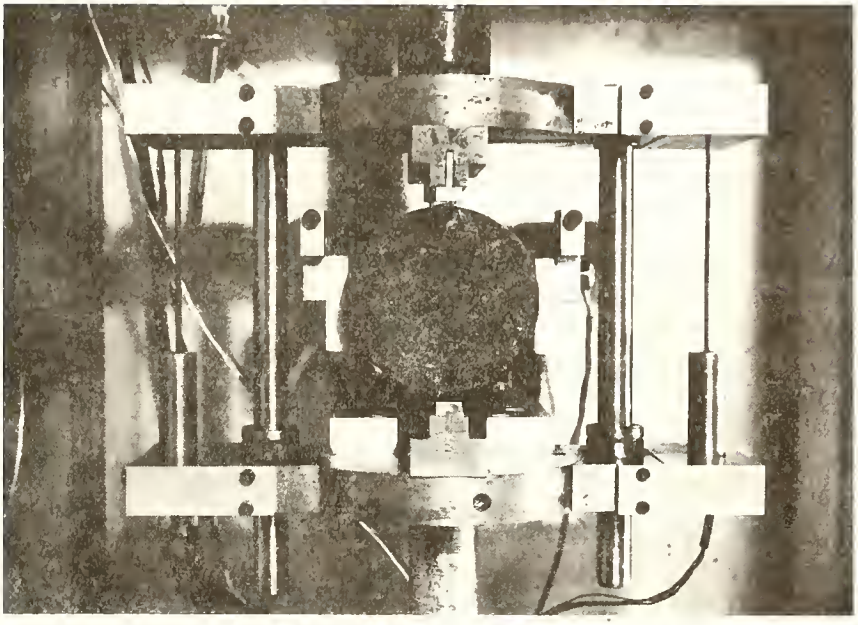


FIGURE 4.3, INDIRECT TENSILE TEST ASSEMBLY

loading strips were curved at the interface with the specimen with a radius of 51 mm (2 in.). Two guide rods were used to prevent any eccentricity in loading. The vertical deformations of the specimen were measured using two identical Linear Variable Differential Transformers (LVDTs). They were fixed in a vertical position on both sides and at equal distances from the specimen. The output voltages of the two LVDTs were connected in series to obtain one output representing the sum of the two voltages. The horizontal deformations, however, were measured using a diametrical extensometer as shown in Figure 4.4. It consisted of two arms touching the specimen across the horizontal diameter. The two arms were allowed to move horizontally by means of two hinged joints. An LVDT was connected in a horizontal position between the two arms to measure the horizontal movement of the arms. The arms were pulled together by means of a light spring. The applied load was measured by means of the load cell which was connected to the load frame. The output voltages of the LVDTs and the load cell were calibrated, by means of a micrometer and a voltmeter, and connected to two X-Y recorders. The X-Y recorders were adjusted to plot load vs. horizontal deformation and vertical deformation vs. horizontal deformation.

4.3.2 Temperature Control

The MTS machine was provided with a temperature controlled chamber, in which the test was performed. A thermometer buried inside a dummy specimen was used to indicate the actual temperature of the specimens. It took between 2-4 hours to change the specimen temperature to the required test temperature. During this period specimens were put in sealed plastic bags to prevent further moisture loss. Also, coating the

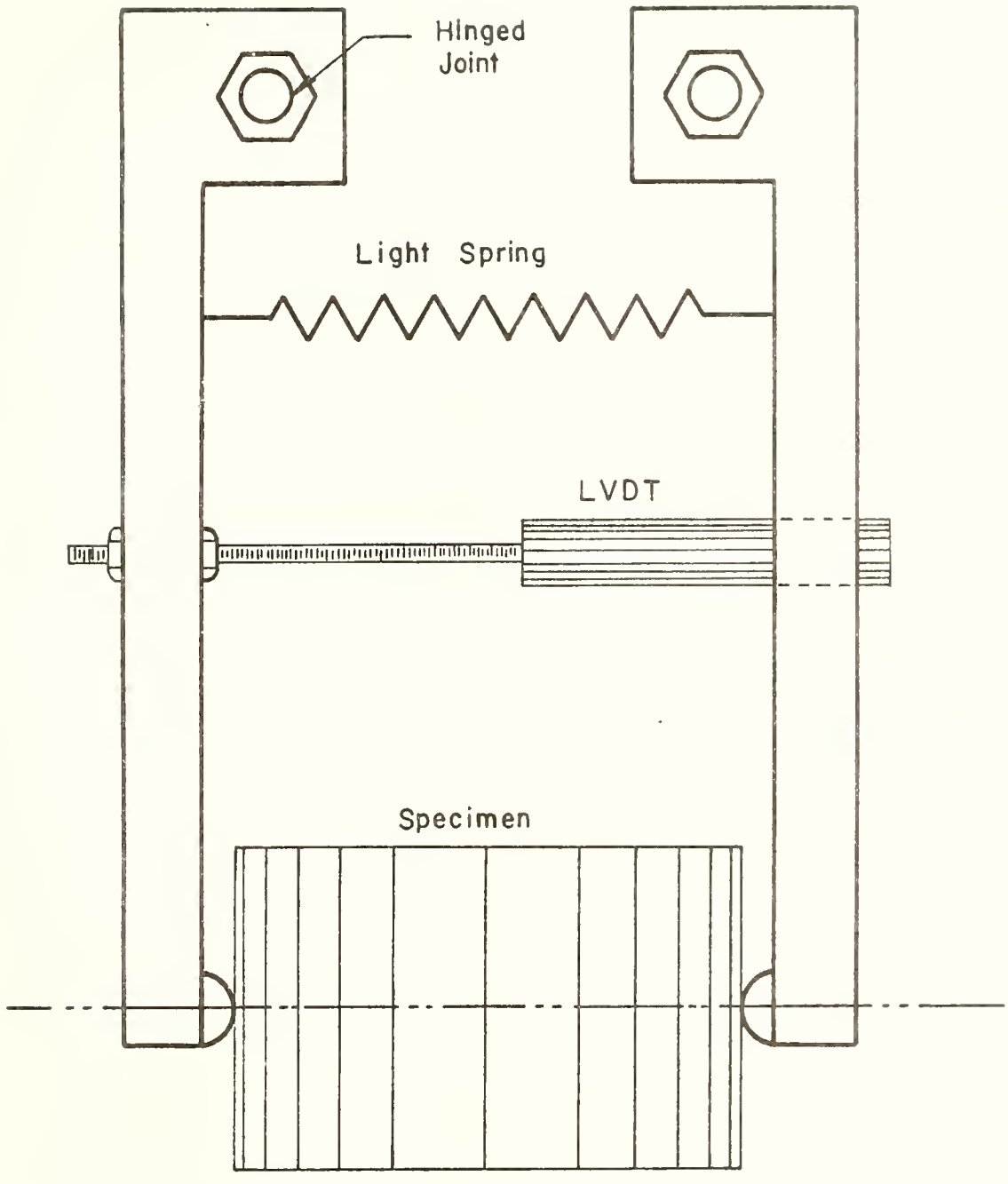


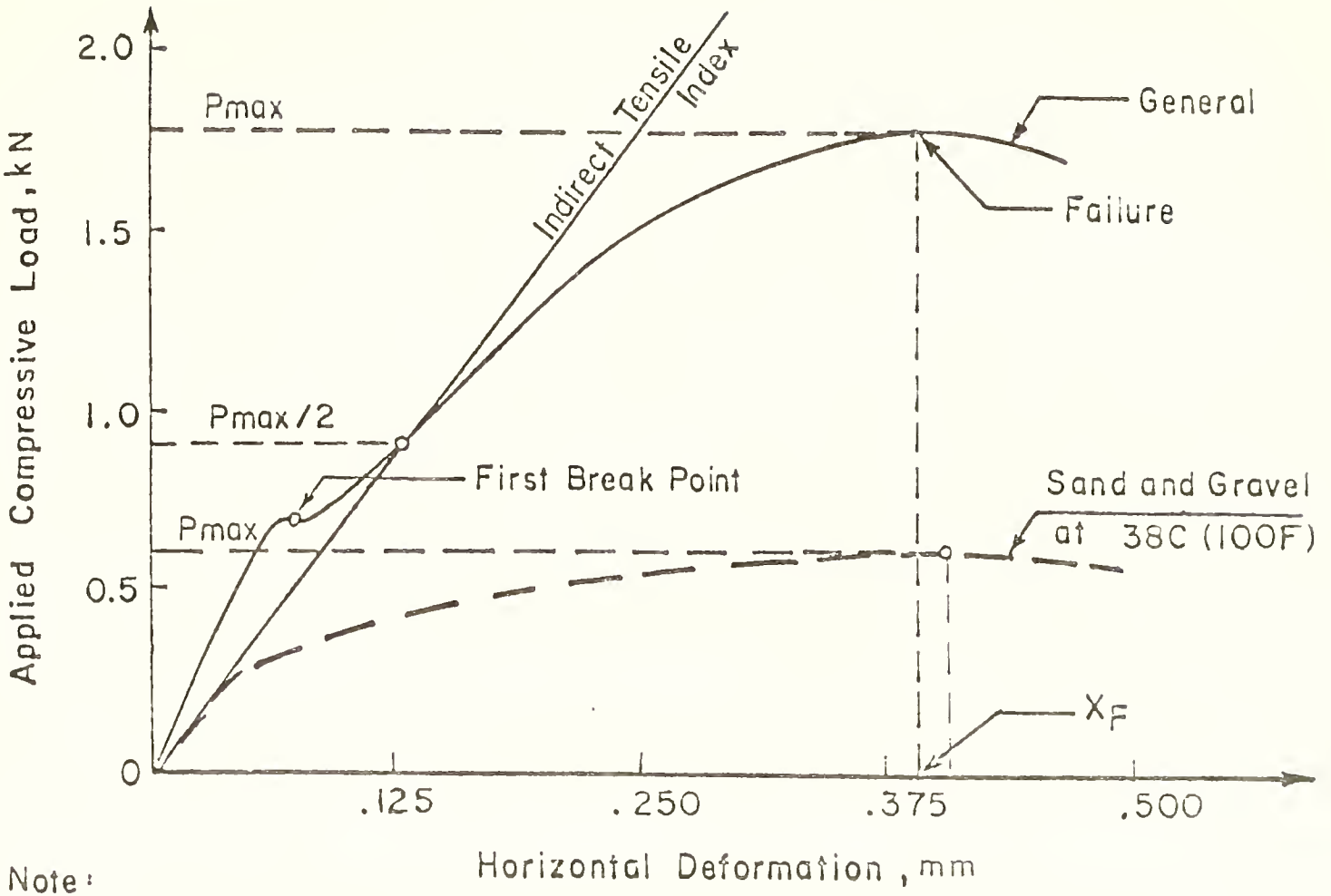
FIGURE 4.4 ,DIAMETRAL EXTENSOMETER

specimens with zinc stearate when the unit weights were determined helped in retaining moisture in the specimens.

4.3.3 Test Procedure

The following is a brief description of the testing procedure which was adopted for the indirect tensile test.

1. When the specimen reached the required test temperature, it was removed from the plastic bag and centered between the two loading strips. The distance between the two loading strips was adjusted to allow a light touch between the specimen and the loading strips before the load was applied.
2. The output voltages of the horizontal and vertical LVDTs were controlled by moving the LVDT cores with respect to the LVDT coils to make sure that they were used within the linear range.
3. The sensitivities of the X-Y recorders were adjusted according to the expected strength of the specimen. Also, the positions of the recording pens were changed to start the recording from the lower left corners of the charts.
4. The load was then applied with a rate of loading of 51 mm (2 in.) per minute till the specimen failed. During the load application, the load versus horizontal deformation and the vertical deformation versus horizontal deformation were recorded on the two X-Y recorder charts (Figure 4.5 and 4.6).
5. After the test was completed specimens were broken apart and dried in a forced draft oven for 24 hours at 110°C (230°F).
6. The oven dried weight was determined and was used to calculate the moisture retained at time of testing and the dry unit weight of the

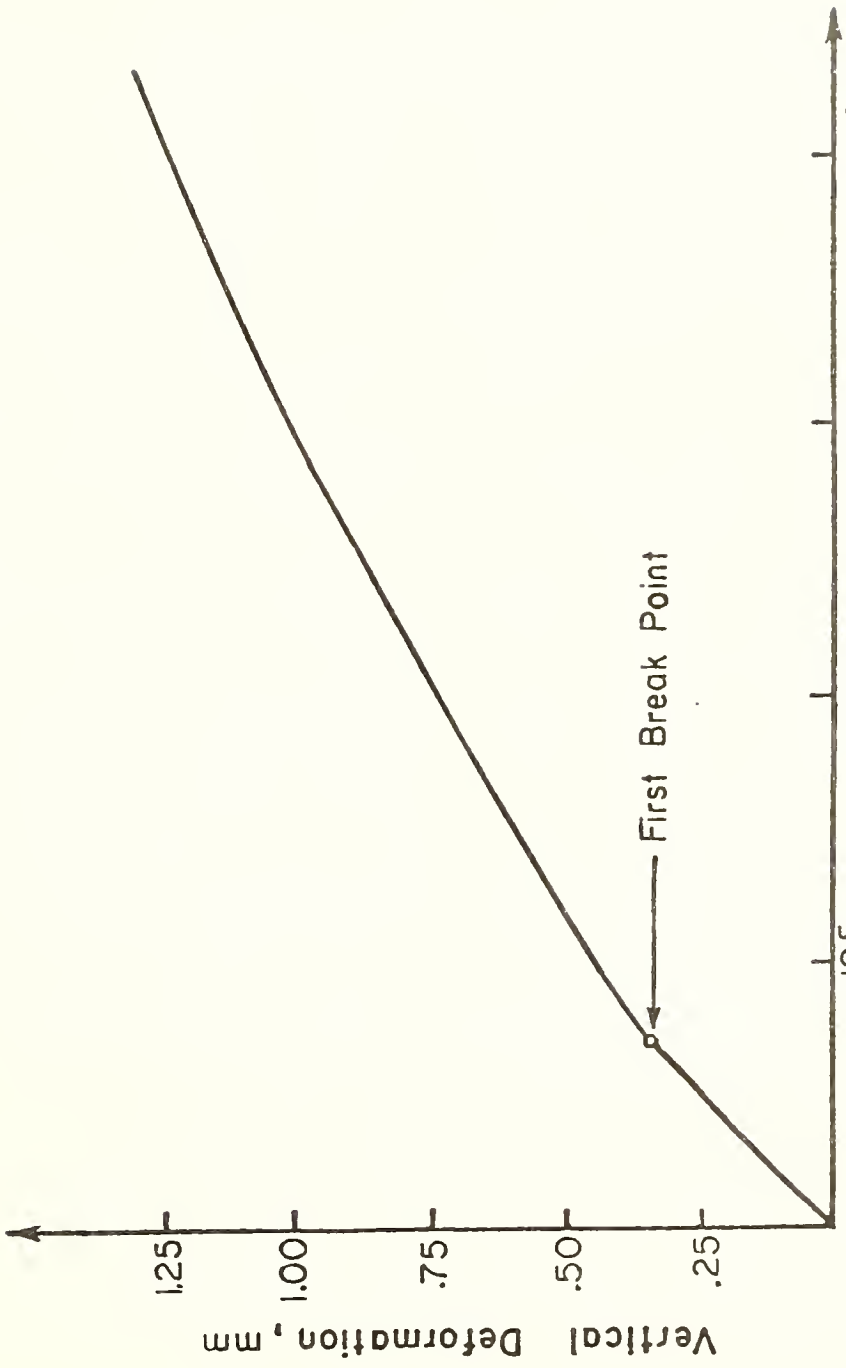


Note:

1 kN=225 lb

1 mm=.039 in.

FIGURE 4.5, LOAD VS. HORIZONTAL DEFORMATION



Note:
1 mm = .039 in.

FIGURE 4.6, VERTICAL DEFORMATION VS. HORIZONTAL DEFORMATION

specimen as presented in Appendix A.

4.4 Analysis of Results

The typical shape of the load vs. horizontal deformation curve is depicted in Figure 4.5. At a certain load there is an increase in the horizontal deformation without increase in load, which is referred to as the first break point (31). When specimens were tested at 10°C (50°F) the first break load was much lower than the maximum load, while at 38°C (100°F) the first break load was much closer to the maximum load. For sand and gravel specimens tested at 38°C (100°F), the first break point was not as evident as shown in Figure 4.5.

The typical curve for vertical deformation vs. horizontal deformation is presented in Figure 4.6. The relationship is fairly close to a straight line. At a point corresponding to the first break the slope of the line is slightly changed. However, in some cases the plot of the vertical deformation vs. horizontal deformation was a continuous curve.

Equations that were used to determine the indirect tensile parameters are shown below. These equations are valid only for the English units and are restricted to 102 mm (4 in.) diameter specimens with a loading strip width of 12.7 mm (1/2 in.) (37,41). If the SI units are used, constants of the equations should be changed.

$$\sigma_{IT} = .156 \frac{P_{max}}{h} \tag{4.1}$$

$$\nu = \frac{0.0673\ DR - 0.8954}{-0.2494\ DR - 0.0156} \tag{4.2}$$

$$E_{IT} = \left(\frac{P}{X}\right)\left(\frac{1}{h}\right)(0.9976\ \nu + 0.2692) \tag{4.3}$$

$$\varepsilon_T = X_T \left(\frac{0.1185\ \nu + 0.03896}{0.2494\ \nu + 0.0673}\right) \tag{4.4}$$

where

σ_{IT} = indirect tensile strength, psi

P_{max} = maximum load at failure, lb

h = specimen height, in.

ν = Poisson's ratio

DR = deformation ratio, the slope of the least square line of best fit between vertical deformation and the corresponding horizontal deformation up to the first break point (in case of no first break point the first portion of the curve was considered).

E_{IT} = indirect tensile stiffness, psi

$\frac{P}{X}$ = the secant modulus at 50% of the first break point on the load vs. horizontal deformation curve, lb/in.

ε_T = total tensile strain at failure, in./in. (the length over which the strain was estimated = 0.004 in.).

X_T = total horizontal deformation at failure, in.

The following sections of this chapter will present a study of the effect of the different factors on each one of the asphalt emulsion mix response (measured) variables. This will be followed by a presentation of the effect of moisture (water sensitivity test) on the performance of the mixture. Typical values of the indirect tensile test results are presented in Appendix C.

4.4.1 Indirect Tensile Strength

The tensile strength is one of the parameters frequently used in the evaluation of pavement materials. It is a measure of the resistance the pavement layer will have for the tensile stresses. In this study, typical values of the indirect tensile strength of the asphalt emulsion mixes ranged between 25 kPa (3.6 psi) and 596 kPa (86.4 psi). This wide range of indirect tensile strength occurred because of the significant effect of test temperature, aggregate type, curing, and percent initial added moisture.

Test temperature proved to be a major factor in determining the tensile strength of the mixture. Increasing the test temperature softens the asphalt emulsion residue and weakens the mixture. The average indirect tensile strength decreased from 327 to 130 and 58.9 kPa (47.4, 18.9, and 8.5 psi) when the test temperatures were 10, 24, and 38°C (50, 75, and 100°F), respectively. It means that an average reduction of 82% in the indirect tensile strength value has occurred when the temperature of the mixture increased from 10 to 38°C (50 to 100°F). Therefore, it can be concluded that the mixture is quite temperature susceptible.

Unlike sand and gravel, the rough surface and angular shape of limestone particles increased the adhesion between aggregate particles and the asphalt emulsion and consequently increased the tensile strength of the mixture. Therefore, the average indirect tensile strength for all sand and gravel mixtures in this phase of the study was 134 kPa (19.5 psi), while for limestone mixtures it was 212 kPa (30.8 psi). In other words, sand and gravel mixtures gave an average strength value of 63% of the average strength of limestone mixtures.

Curing increased the tensile strength of the mixture. The indirect tensile strength at 3-day oven curing was always larger than the indirect tensile strength at one-day air curing. This is due to the fact that curing breaks the asphalt emulsion allowing water to evaporate leaving the asphalt residue adhering to the aggregate particles. At 1-day air curing which represented the curing condition in the field after construction, the average indirect tensile strength was 136 kPa (19.7 psi). However, at 3-day oven curing which was representative of the long-term curing of the mixture, the average indirect tensile strength was 211 kPa (30.6 psi).

Increasing the initial added moisture, to some extent, helps the asphalt emulsion in coating the aggregate particles. However, in most combinations higher indirect tensile strengths were obtained by adding 3% initial moisture rather than 4.5%. The optimum initial added moisture which gave high strength values depended on its interaction with other factors.

The interaction of aggregate type, curing and test temperature had a significant affect on the indirect tensile strength as shown in Figure 4.7. The highest average value of the indirect tensile strength occurred using limestone at a test temperature of 10°C (50°F) and oven curing. The lowest average strength was obtain using sand and gravel mixtures at a test temperature of 38°C (100°F) and one-day air curing.

4.4.2 Poisson's Ratio

Poisson's ratio in the classical sense is defined as the ratio of the lateral strain to the axial strain, caused by an axial load. Using the diametral load, similar Poisson's ratio values may be obtained. In

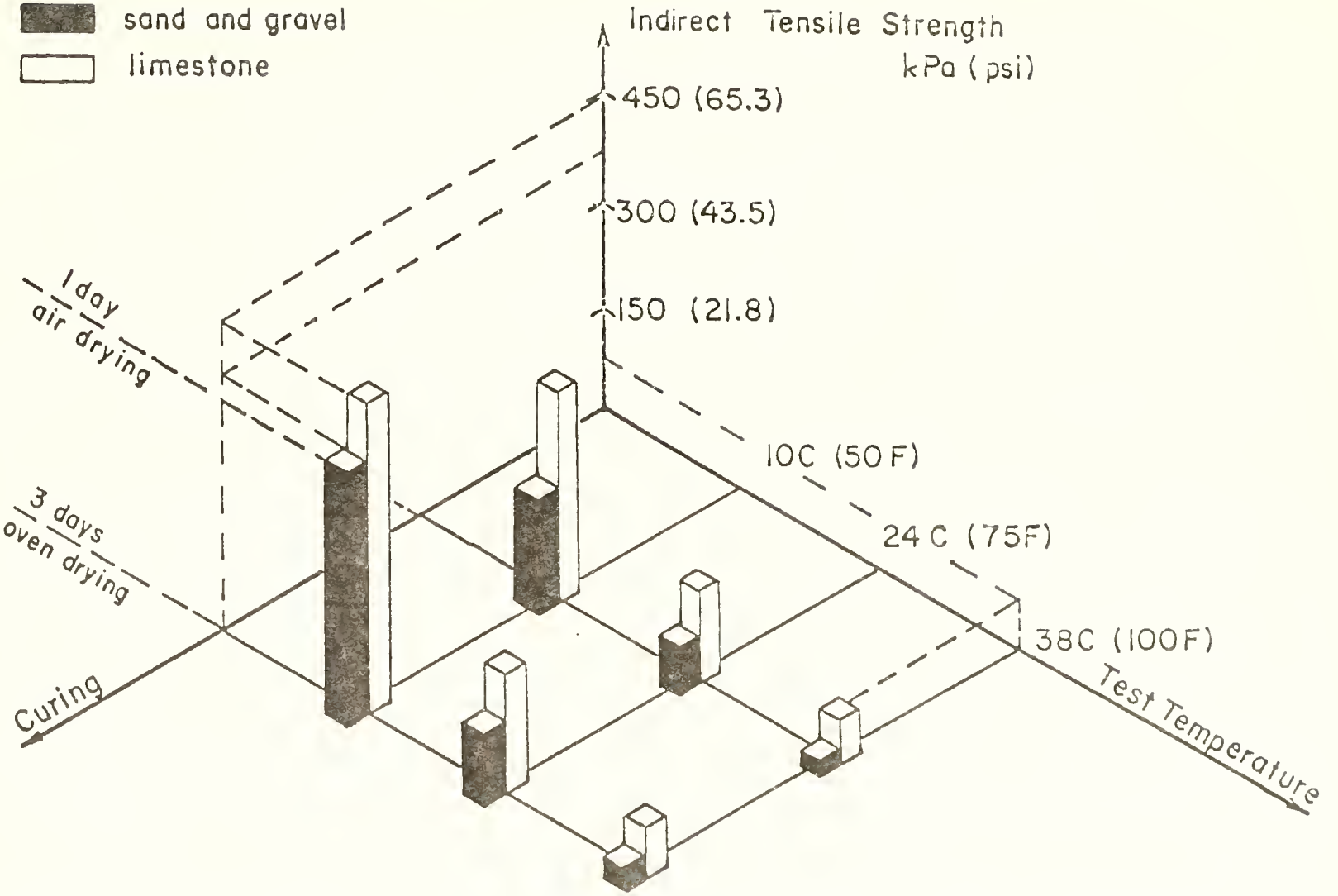


FIGURE 4.7 ,INFLUENCE OF AGGREGATE TYPE, CURING AND TEST TEMPERATURE ON INDIRECT TENSILE STRENGTH

this study, Poisson's ratio was very sensitive to test temperature. When the test temperature increased, Poisson's ratio increased. A small number of Poisson's ratios were negative at the 10°C (50°F) test temperature. However, at a test temperature of 38°C (100°F) most of Poisson's ratio values exceeded 0.5. It was obvious that the asphalt emulsion mixtures did not totally meet the initial assumptions in the original derivations of the equations at 38°C (100°F). In fact, at a high test temperature, the specimen began to develop hair-line cracks before total failure. These tension cracks, caused a significant increase in volume which explains the value of Poisson's ratio being larger than 0.5. A previous study (62) used the term strain ratio rather than Poisson's ratio, which is suitable at high temperatures. Therefore, in the calculation of the indirect tensile stiffness and strain, it is recommended that Poisson's ratio should not be determined using the indirect tensile test at high temperatures. In the rest of the analysis Poisson's ratio was assumed to be 0.3, 0.35, and 0.4 at test temperatures of 10, 24, and 38°C (50, 75, and 100°F) respectively.

In addition to test temperature, curing had an effect on the obtained Poisson's ratio. At one-day air curing, specimens were not firm enough and, consequently, Poisson's ratio was high. At 3-day oven curing, specimens had low values of Poisson's ratio. Other factors did not significantly affect values of Poisson's ratio.

4.4.3 Indirect Tensile Stiffness

The stiffness characteristics of the asphalt treated mixtures are very important not only to assess the behavior of the mixtures itself, but also to evaluate the performance of the highway pavement. The in-

direct tensile stiffness is analogous to the modulus of elasticity, E, in the classical sense (36). At very short times of loading and/or low temperatures, the behavior of the asphalt treated mixture is almost elastic which is one of the assumptions in the indirect tensile test theory.

At low temperatures, shrinkage cracks tend to develop in highway asphaltic pavement. The greater the tensile stiffness of the asphaltic mixture, the larger the thermal stresses developed in the pavement by temperature changes. Low stiffness values for asphalt mixtures are desired for good low temperature performance in order to eliminate or reduce such cracks. However, at high temperatures, high stiffness values are needed to reduce excessive deformation within the pavement or rutting. In general, low temperature susceptible asphaltic mixtures are needed to improve the highway pavement performance throughout the different seasons.

Using the indirect tensile test, the tensile stiffness values which were determined using the obtained Poisson's ratios varied widely between 24 MPa (3.5 ksi) and 2068 MPa (300 ksi). While the stiffness values obtained by assuming Poisson's ratios equal 0.3, 0.35, and 0.4 at test temperatures of 10, 24, and 38°C (50, 75, and 100°F) respectively varied between 17 MPa (2.4 ksi) and 2482 MPa (360 ksi) for all specimens in the study.

Stiffness values using the assumed Poisson's ratios were greatly affected by temperature. As test temperature increased, stiffness decreased to a very low value. Average stiffness values of 752, 114, and 58 MPa (109.0, 16.6, and 8.4 ksi) were obtained at temperatures of 10,

24, and 38°C (50, 75, and 100°F) respectively. Therefore, a reduction of 85% in the average stiffness value of the AEM has occurred when the temperature increased from 10 to 24°C (50 to 75°F), while a reduction of 92% has occurred by increasing the temperature from 10 to 38°C (50 to 100°F).

In addition to test temperature, the stiffness also was largely affected by the interaction of test temperature, percent asphalt emulsion content and aggregate type as shown in Figure 4.8. No trend can be obtained for the effect of percent asphalt emulsion content or aggregate type. At some combinations, sand and gravel mixtures had higher stiffnesses than limestone mixtures, while at other combinations the opposite was true. The significant effect of aggregate type was apparent at the 10°C (50°F) test temperature. The highest stiffness values were obtained using limestone and 3.25% asphalt emulsion residue content at the 10°C (50°F) test temperature.

The indirect tensile stiffness provided a good correlation with the indirect tensile strength. The correlation coefficient between the indirect tensile stiffness and strength was 0.756 for the 144 specimens tested in this part of the study.

4.4.4 Total Tensile Strain at Failure

Failure tensile strain is a very important parameter used for the asphalt emulsion mixture characterization because it is associated with the cracking of the highway pavement. The occurrence of cracking was found to increase as the failure strain decreased (36). Therefore, one of the objectives of this study was to determine the the total tensile strain at failure for the AEM for the different variables. The total

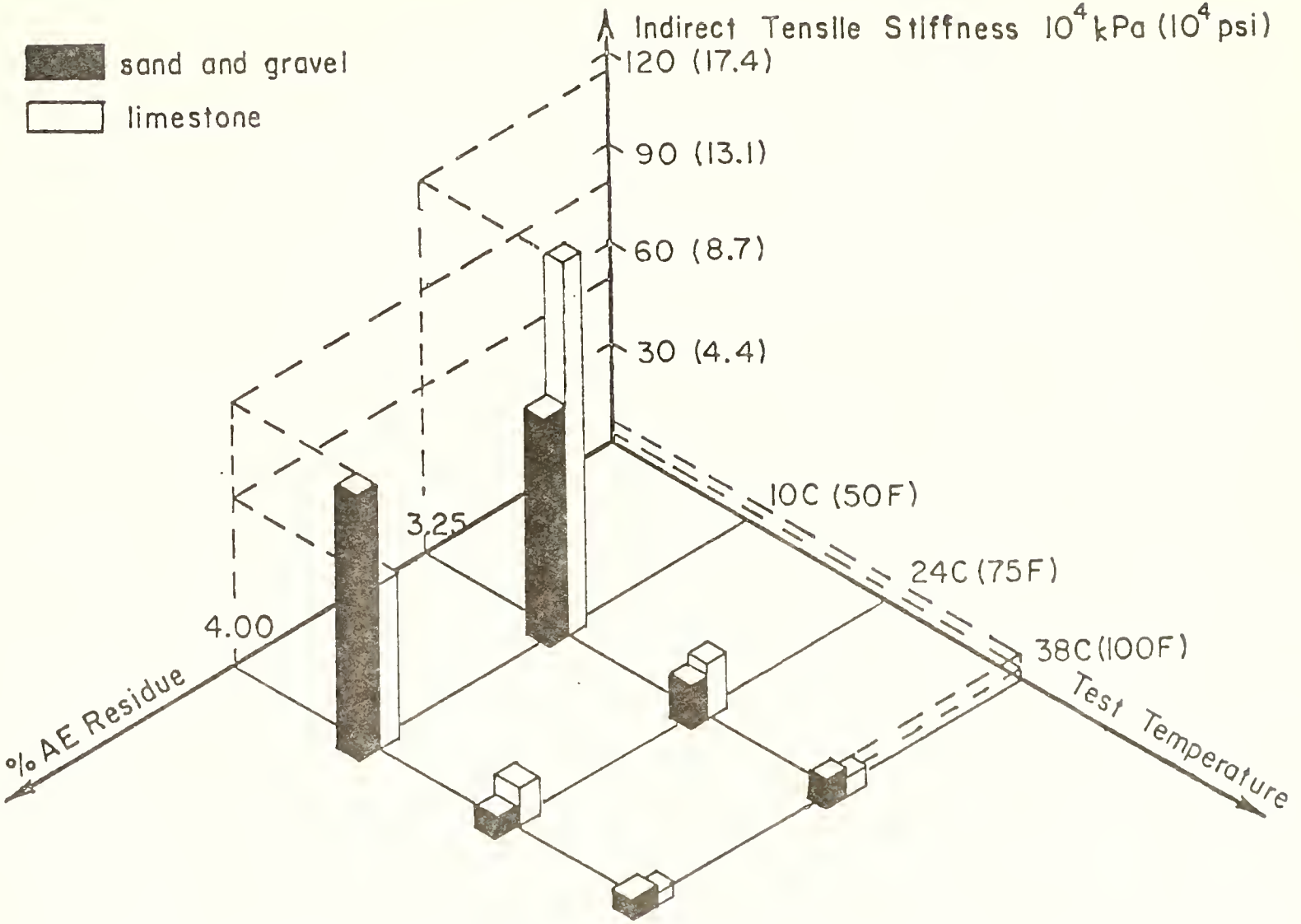


FIGURE 4.8, STIFFNESS AS A FUNCTION OF PERCENT ASPHALT EMULSION, TEST TEMPERATURE AND AGGREGATE TYPE

tensile strain at failure varied between 5.8×10^{-3} and 11.9×10^{-3} mm/mm (in./in.). During calculation of the total tensile strain at failure, Poisson's ratio values were assumed to be 0.3, 0.35, and 0.4 at temperatures of 10, 24, and 38°C (50, 75, and 100°F) respectively.

According to the ANOVA results, the asphalt emulsion content had an effect on the total tensile strain at failure. Asphalt emulsion can act as a lubricant between the aggregate particles. Thus, high tensile strains at failure were obtained using high asphalt emulsion contents. The average tensile strain at failure was 8.0×10^{-3} mm/mm (in./in.) for mixtures containing 3.25% asphalt emulsion residue, while it was 9.3×10^{-3} mm/mm (in./in.) for mixtures containing 4% asphalt emulsion residue. In addition to the asphalt emulsion content, the tensile strain at failure was affected by curing. Curing increased the rigidity of the mixture because it allowed the emulsion to break. Therefore, it decreased the value of the total tensile strain at failure. Average tensile strains of 9.1×10^{-3} and 8.2×10^{-3} mm/mm (in./in.) were obtained for air cured and oven cured mixtures respectively. Meanwhile, the test temperature affected the total tensile strain at failures. The largest value of the tensile strain was obtained at the intermediate test temperature. The effect of curing, asphalt emulsion content and test temperature on the total tensile strain at failures is shown in Figure 4.9.

4.4.5 Indirect Tensile Index

The indirect tensile index (Figure 4.5) varied between 0.8 and 119 kN/mm (4.5×10^{3} and 680×10^{3} lb/in.). It was very sensitive to test temperature. As test temperature increased, the indirect tensile index decreased markedly. The average indirect tensile index value was 34.1,

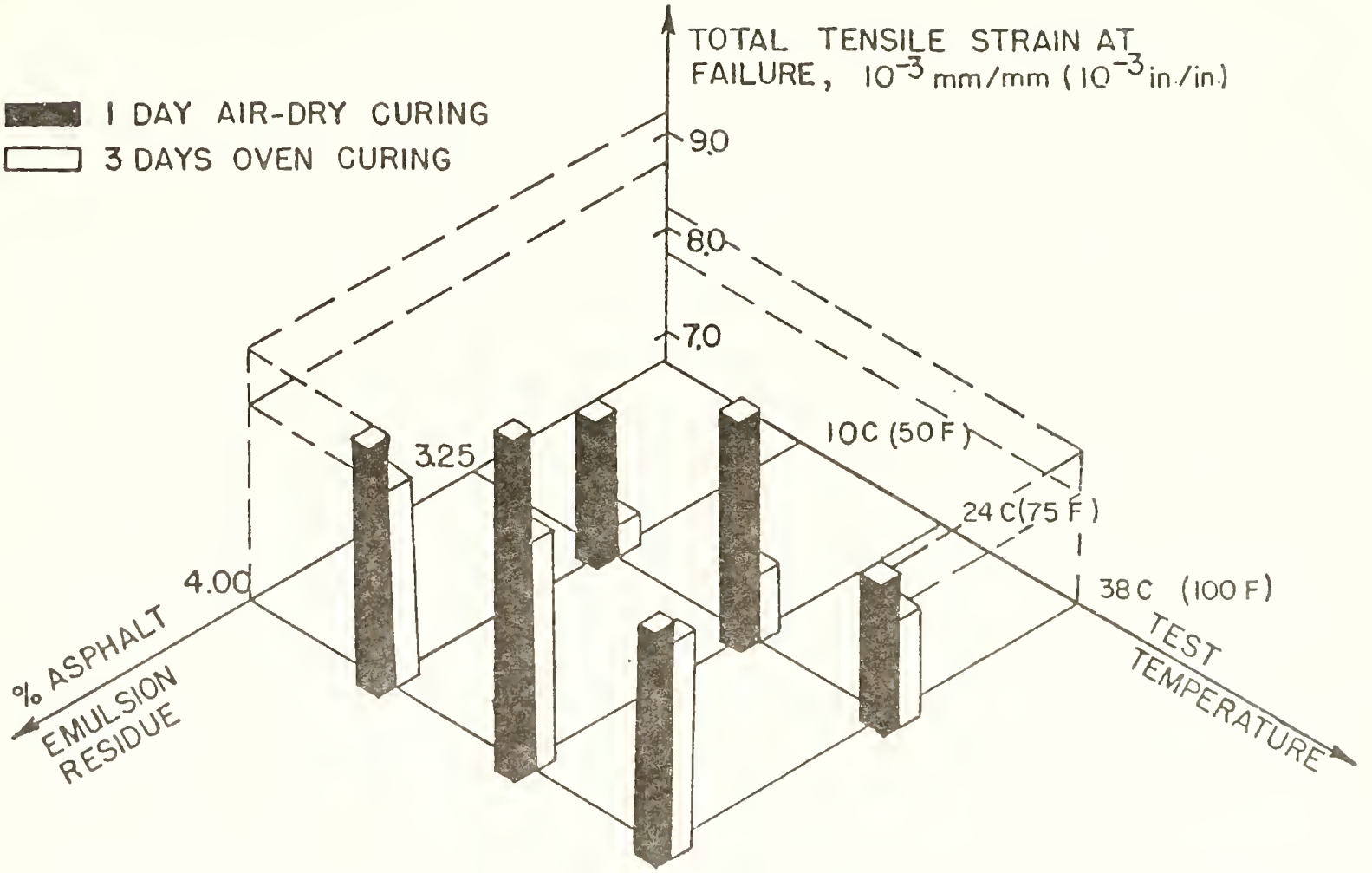


FIGURE 4.9 ,EFFECT OF CURING, ASPHALT EMULSION CONTENT AND TEST TEMPERATURE ON TOTAL TENSILE STRAIN AT FAILURE

8.8, and 3.9 kN/mm ($195x10^3$, $50x10^3$ and $22x10^3$ lb/in.) at test temperatures of 10, 24, and 38°C (50, 75, and 100°F) respectively. In addition to test temperature, aggregate type and asphalt emulsion content had an effect on the indirect tensile index. Limestone mixtures always gave larger indices than sand and gravel mixtures. Also, a 3.25% asphalt emulsion residue content gave higher index values than a 4% asphalt emulsion residue content. The interaction effect of test temperature, aggregate type and asphalt emulsion content is presented in Figure 4.10.

The indirect tensile index values provided a good correlation with the test temperature, and asphalt emulsion content. The indirect tensile index average values took a consistant trend for the different factor combinations as shown in Figure 4.10. Also, the indirect tensile index is independent of Poisson's ratio. This leads to the conclusion that using the indirect tensile index in conjunction with other parameters such as the indirect tensile strength could provide a good characterization of the asphalt emulsion treated mixture.

4.4.6 Unit Weight at Time of Compaction

The unit weight at time of compaction, which is a measure of the compactability of the asphalt emulsion mixture during the field construction, is a useful parameter in the mixture evaluation. High unit weights achieved during construction are recommended in order to reduce further compaction by traffic that results in rutting of the pavement. On the other hand, a certain amount of air voids in the mixture is needed to increase drainage and curing rate. In this study, the typical unit weights of the mixture at time of compaction ranged from 2348 kg/m^3 (147.3 pcf) to 2466 kg/m^3 (152.8 pcf). Both asphalt emulsion content

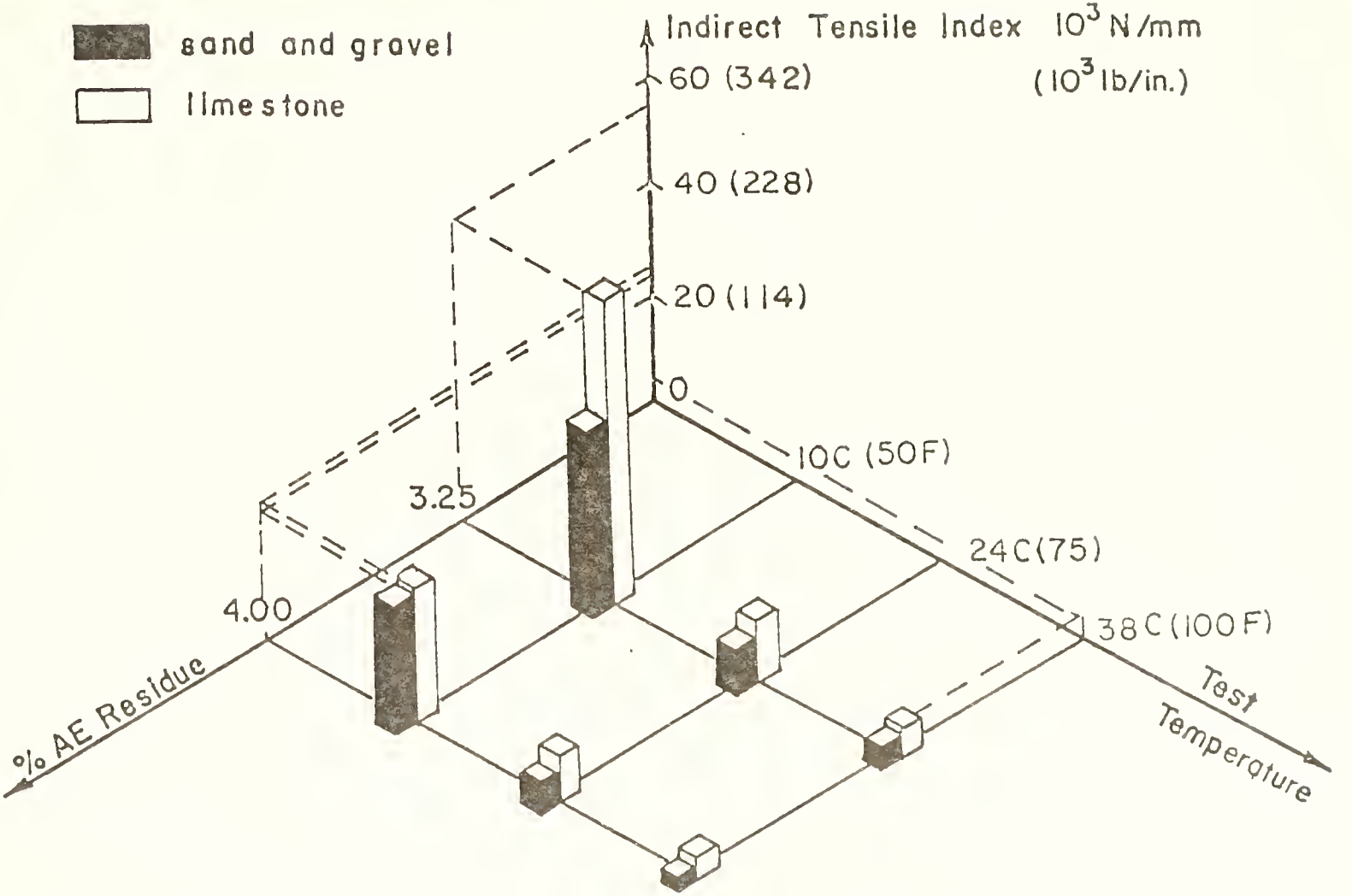


FIGURE 4.10, INDIRECT TENSILE INDEX AS A FUNCTION OF PERCENT ASPHALT EMULSION, TEMPERATURE AND AGGREGATE TYPE

and percent initial added moisture affected the compactability of the mixture. Increasing, the asphalt emulsion content and/or percent initial added moisture increases the lubrication between the aggregate particles. This allows aggregate particles to move smoothly during compaction to decrease the air voids and increase the unit weight of the mixture as well. At the same time both asphalt emulsion and moisture fill the air voids between aggregate particles. The average unit weights at time of compaction for the different asphalt emulsion contents and initial added moistures are presented in Table 4.2

Table 4.2 Average Unit Weights of the AEM at Time of Compaction, kg/m^3 (pcf)

%Initial added Moisture	%Asphalt Emulsion Residue 3.25	4.00
3.0	2385(148.8)	2418(150.9)
4.5	2405(150.1)	2426(151.4)

The interaction of asphalt emulsion content, percent initial added moisture and aggregate type had a significant effect on the compactability of the mixture (Figure 4.11). Limestone mixtures with 4% asphalt emulsion residue content and 4.5% initial added moisture gave the highest average unit weight after compaction which is satisfactory in design.

4.4.7 Unit Weight at Time of Testing

The wet unit weight of the specimen at time of testing including the moisture portion represents the unit weight of the mixture in the field after some curing. It varied from 2312 to 2450 kg/m^3 (144.3 and

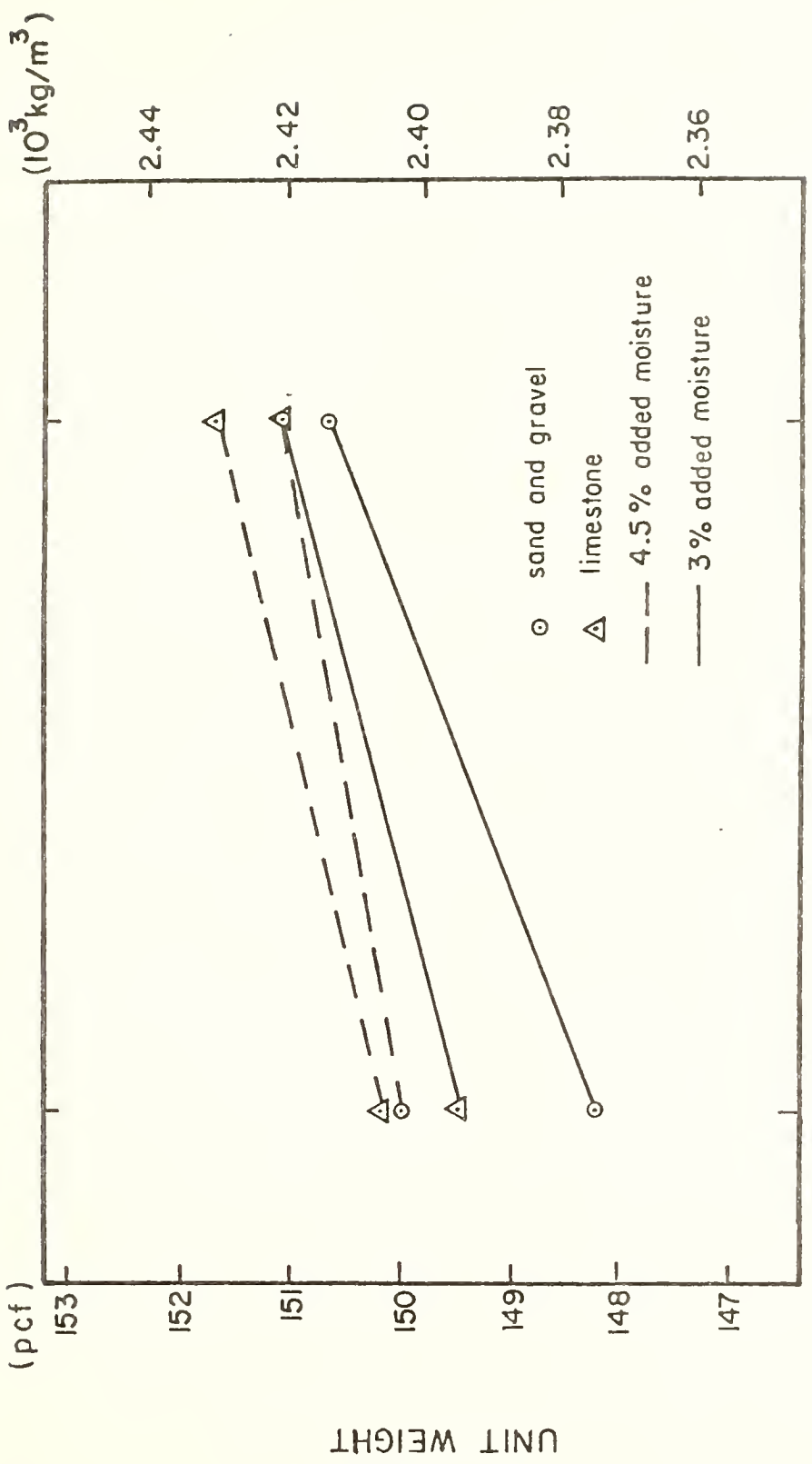


FIGURE 4.11, EFFECT OF PERCENT ASPHALT EMULSION, AGGREGATE TYPE AND PERCENT ADDED MOISTURE ON UNIT WEIGHT AT TIME OF COMPACTION

152.8 pcf) with an average of 2389 kg/m^3 (149.1 pcf) for all mixtures included in the study. The wet unit weight at testing time was mainly affected by asphalt emulsion content, curing level and type of aggregate (Figure 4.12). Increasing the asphalt emulsion content helps in filling the air voids in the mixture. It also helps in lubricating the mixture allowing more compaction which increased the wet unit weight. However, more curing allows moisture to leave the mixture and decreases the wet unit weight. In addition, limestone mixtures gave higher wet unit weights than sand and gravel mixtures.

The dry unit weight of the specimen excluding the moisture portion ranged between 2301 and 2424 kg/m^3 (143.6 and 151.3 pcf) with an average of 2364 kg/m^3 (147.5 pcf) for all specimens in the study. It was largely affected by the asphalt emulsion content and aggregate type. It was not affected by curing, as expected, because regardless of the amount of moisture that leaves the specimen during curing, the oven-dried weight of the specimen remained the same and the dry unit weight remained the same also. The effects of asphalt emulsion content and aggregate type took the same trend as the case of the wet unit weight. The average day unit weight increased from 2353 to 2375 kg/m^3 (146.8 and 148.2 pcf) when the asphalt emulsion residue contents were 3.25 and 4% by weight of dry aggregate respectively. Also, the average dry unit weight was 2345 kg/m^3 (146.3 pcf) for sand and gravel mixtures and 2382 kg/m^3 (148.6 pcf) for limestone mixtures.

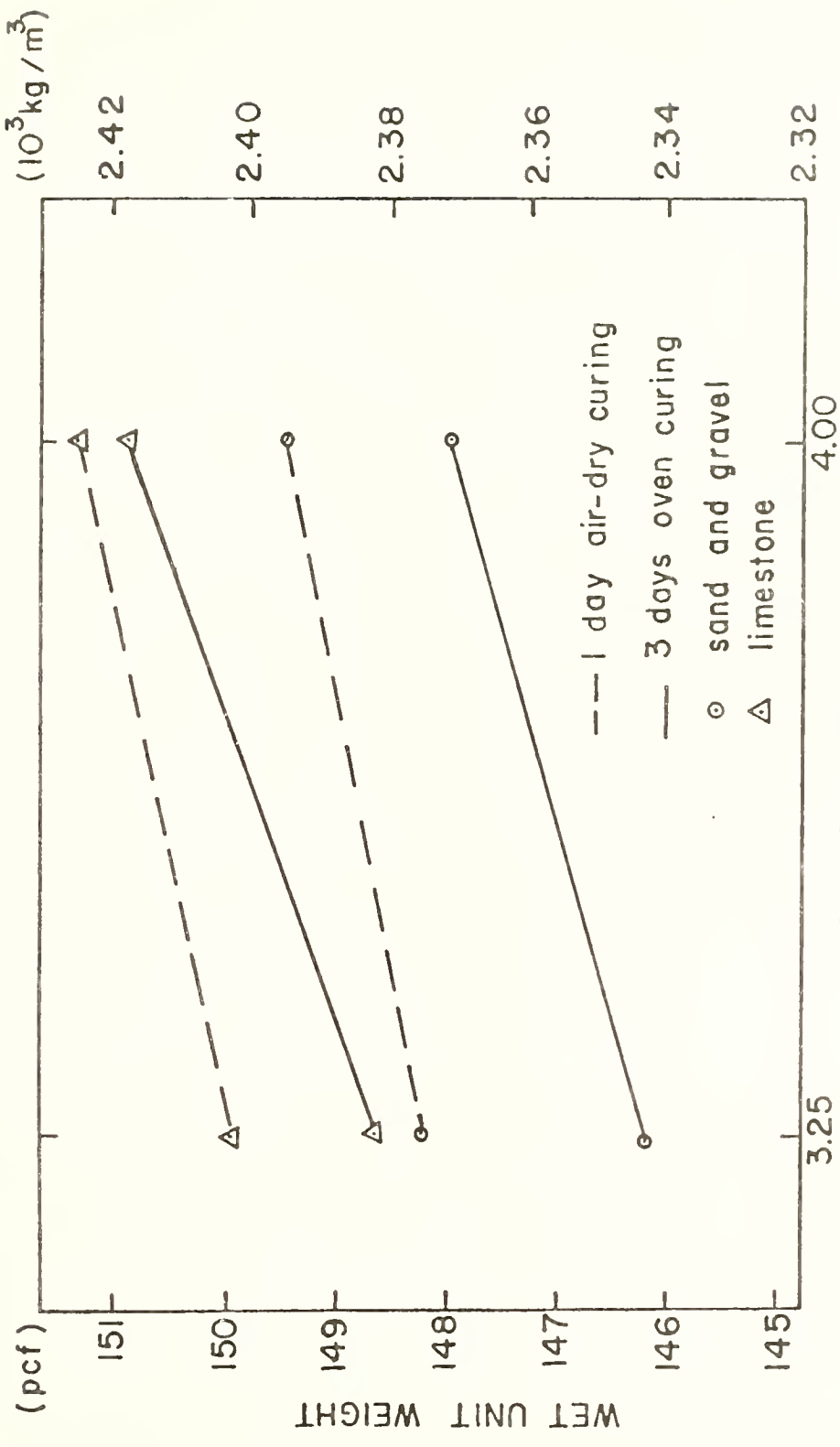


FIGURE 4.12, EFFECT OF ASPHALT EMULSION CONTENT, AGGREGATE TYPE AND CURING ON WET UNIT WEIGHT AT TIME OF TESTING

4.4.8 Moisture Retained at Time of Testing

The main function of the moisture in the cold mixed AEM is to enhance the workability of the mix and to improve the aggregate coating with asphalt residue during the mixing operation. During the curing process, the water evaporates leaving the asphalt residue adhering to the surface of the aggregate particles. The amount of moisture retained in the mixture is a measure of the degree of curing.

In this study, the amount of moisture retained at time of testing ranged between 0.25% and 2.20% of the dry weight of aggregate. It was mainly affected by curing as well as asphalt emulsion content. The average retained moisture was 1.6% for 1-day air cured mixtures, while it was 0.7% for 3-day oven cured mixtures. Also, when the asphalt emulsion residue content increased from 3.25 to 4%, the moisture retained in the mixture increased from 1.0 to 1.3%.

The effect of curing, asphalt emulsion content and aggregate type upon percent retained moisture is illustrated in Figure 4.13. It is apparent that oven-cured specimens had much lower percent moisture than air-dried specimens. Also, the percent retained moisture was higher for the 4% asphalt emulsion residue than for the 3.25% asphalt emulsion residue especially for oven curing versus air curing.

4.4.9 Total Liquid at Time of Testing

The total liquid in the asphalt emulsion treated mixture is the sum of the asphalt emulsion residue content and the amount of retained moisture. It is one of the parameters frequently used in the asphalt emulsion mixture evaluation. The average total liquid of all specimens tested in the study was 4.8% by weight of the dry aggregate. It ranged

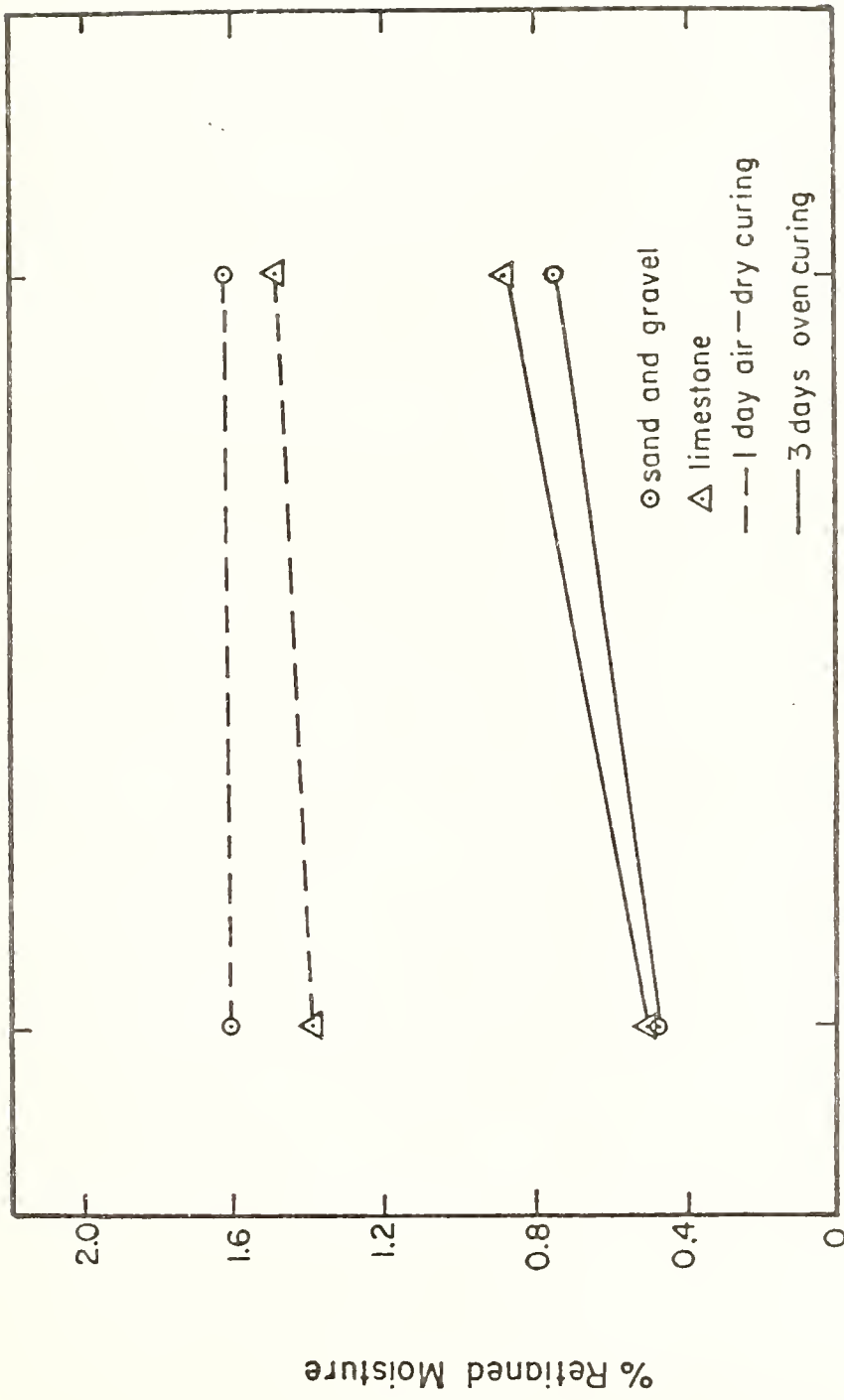


FIGURE 4.13, EFFECT OF PERCENT ASPHALT EMULSION, AGGREGATE TYPE AND CURING ON PERCENT MOISTURE RETAINED AT TIME OF TESTING

between 3.5% and 6.0% due to the effect of the different factors.

The total liquid in the mixture at time of testing (after curing) was largely affected by curing condition and asphalt emulsion content. Curing allows moisture to evaporate which decreases the amount of total liquid. Also, increasing the asphalt emulsion increases the liquid content of the mixture and decreases the rate of moisture loss during curing. The average total liquid of all specimens in the study decreases from 5.2% to 4.3% when the curing condition changed from 1-day air curing to 3-day oven curing. Meanwhile, increasing the asphalt residue content from 3.25 to 4% increased the average amount of total liquid from 4.3 to 5.2% by weight of the day aggregate.

4.4.10 Voids at Time of Testing

a. Air Voids

Minimum air voids are desired to reduce rutting or excessive deformation by traffic, and also to reduce moisture absorption which affects the stripping potential. On the other hand, a certain amount of air voids is needed to enhance the rate of curing of the mixture and to improve the drainage of the pavement.

The air voids for all specimens used in the indirect tensile study ranged between 2.56% and 9.80% of the total volume with an average of 5.50%. The percent air voids at time of testing was markedly affected by the asphalt emulsion content and curing time. It decreased from 6.68% to 4.32% by increasing the percent asphalt residue content from 3.25 to 4% by weight of dry aggregate. The reason for this is that the asphalt emulsion replaces air voids and allows more compaction as well. It was also found that curing had a marked effect on increasing percent

air voids because curing allowed water to leave the mixture. For 1-day air curing, the average air voids was 4.44% of the total volume, while it was increased to 6.56% for 3-day oven curing.

The interaction of curing, initial added moisture and aggregate type was found to have a significant affect on the amount of air voids in the mixture. Different combinations of this interaction had different effects on the air voids as illustrated in Figure 4.14. The maximum values of air voids were obtained for sand and gravel mixtures at 3-day oven curing for both 3 and 4.5% initial added moistures.

b. Total Voids

The total voids in the asphalt emulsion mixture at time of testing are the sum of air voids and voids filled with moisture. They are one of the parameters used to evaluate the mixture, as it affects the density and permeability of the mixture as well as the potential for rutting or excessive deformation by traffic. The total voids at time of testing varied between 5.80 and 10.51% of the total volume for all specimens in the indirect tensile test study.

The total voids at time of testing were affected mainly by the asphalt residue content. Increasing the asphalt residue content from 3.25 to 4% decreased the total voids from 9 to 7.2% of the total volume. The total voids were not affected by curing because curing allows water to leave the mixture but the total voids remains the same.

c. Voids in the Mineral Aggregate (VMA)

The voids in the mineral aggregate, VMA, are the volume of intergranular void space between the aggregate particles in a compacted paving mixture that includes the air voids, the effective asphalt emulsion

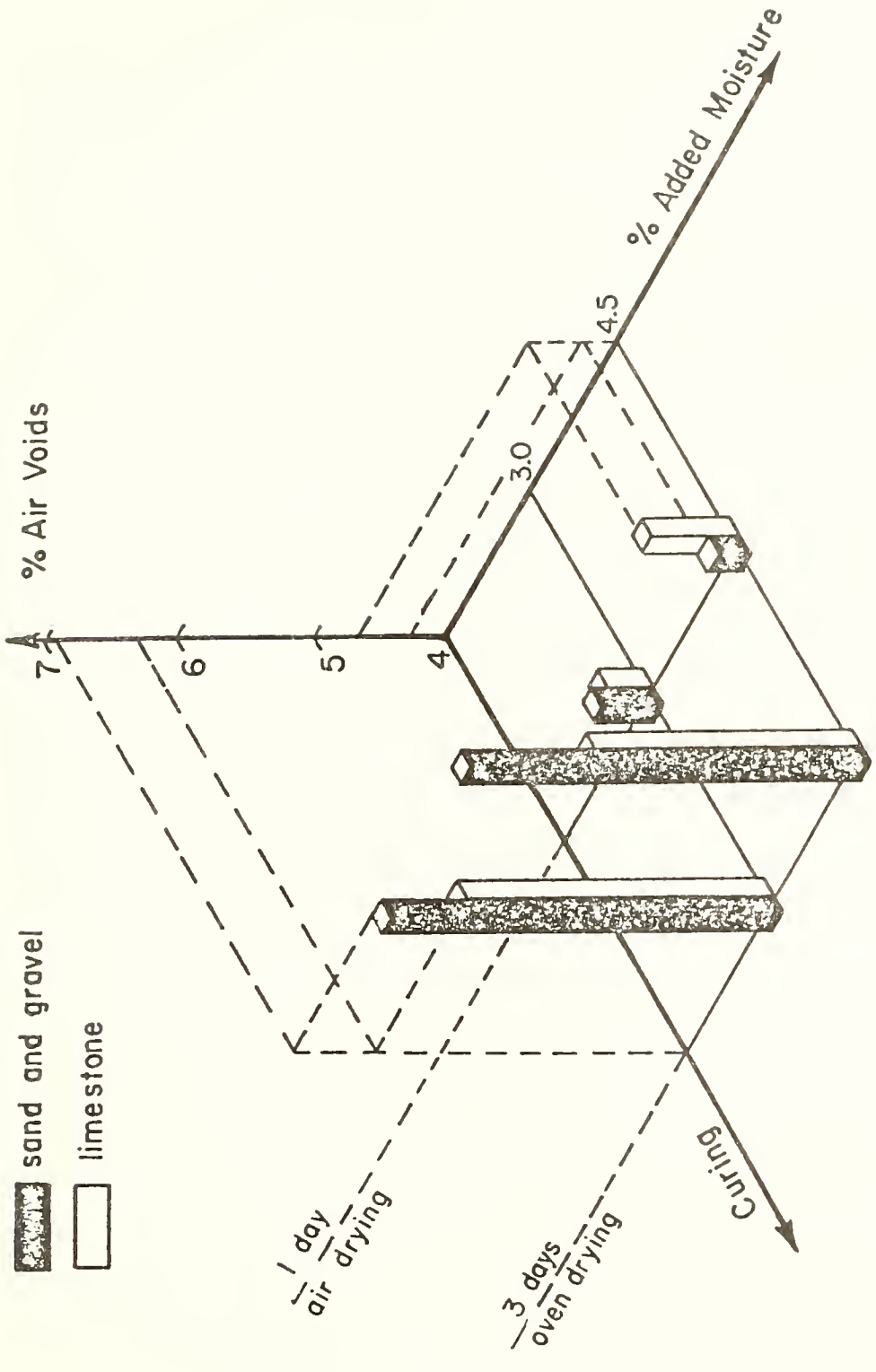


FIGURE 4.14, PERCENT AIR VOIDS AT TIME OF TESTING AS A FUNCTION OF CURING, PERCENT ADDED MOISTURE AND AGGREGATE TYPE

residue and the moisture retained in the mixture, expressed as a percent of the total volume of the sample. In this study, the VMA at time of testing varied between 15.00 and 17.68% of the total volume with an average of 16.29% for all specimens. It was not significantly affected by the variables considered in the study at a level of significance of 5%.

4.4.11 Effect of Aggregate Gradation on the Asphalt Emulsion Mixture Properties

The effect of aggregate gradation was investigated by evaluating a few numbers of specimens prepared with coarse graded aggregate, CG (Figure 3.1). Both sand and gravel and limestone mixtures were used. The asphalt emulsion contents were 3.25 and 4% by weight of the dry aggregate. The initial added moisture content evaluated in this part of the study was 4.5%. Specimens were cured in the oven for 3 days at 49° C (120° F). Three replicates of each factor combination were evaluated using the indirect tensile test. One test temperature was considered which was 24° C (75° F). A comparison was made between the mixture properties of the coarse graded specimens and the corresponding medium graded specimens which were investigated in the previous sections of this chapter. The effect of aggregate gradation on the different asphalt emulsion mixture properties is shown below:

a. Indirect Tensile Test Results

Medium graded specimens gave higher indirect tensile strengths than coarse graded specimens. The average indirect tensile strength of the medium graded specimens was 148.7 kPa (21.6 psi) as compared to 132.3 kPa (19.6 psi) for the corresponding coarse graded specimens. For lime-

stone mixtures, the difference in strength between medium and coarse graded specimens was large compared to sand and gravel specimens as depicted in Figure 4.15. In addition, the medium graded specimens were affected by the asphalt emulsion content in the same manner as the coarse graded mixtures. Increasing the asphalt residue content from 3.25 to 4% slightly decreased the average indirect tensile strength values. Moreover, limestone mixtures gave higher indirect tensile strength values than sand and gravel mixtures.

The effect of aggregate gradation on the indirect tensile stiffness for the different asphalt emulsion contents and aggregate types is represented in Figure 4.16. The highest indirect tensile stiffness values were obtained for medium graded limestone specimens with 3.25% asphalt residue content. In addition to stiffness, the indirect tensile index displayed the same trend as the indirect tensile stiffness.

The effect of aggregate gradation on the total tensile strain at failure was also investigate. Medium graded mixtures were found to have slightly higher total tensile strans at failure than coarse graded mixtures in most cases. The average total tensile strain at failure was 0.0086 and 0.0082 mm/mm (in./in.) for medium and coarse graded mixtures respectively.

b. Unit Weights

The maximum density curve for the aggregate gradation is closer to the medium gradation than the coarse gradation as may be seen in Figure 3.1. Therefore, the unit weight after compaction was higher for medium graded specimens than for coarse graded specimens. The average unit weight of the medium graded specimens after compaction was 2410 kg/m^3

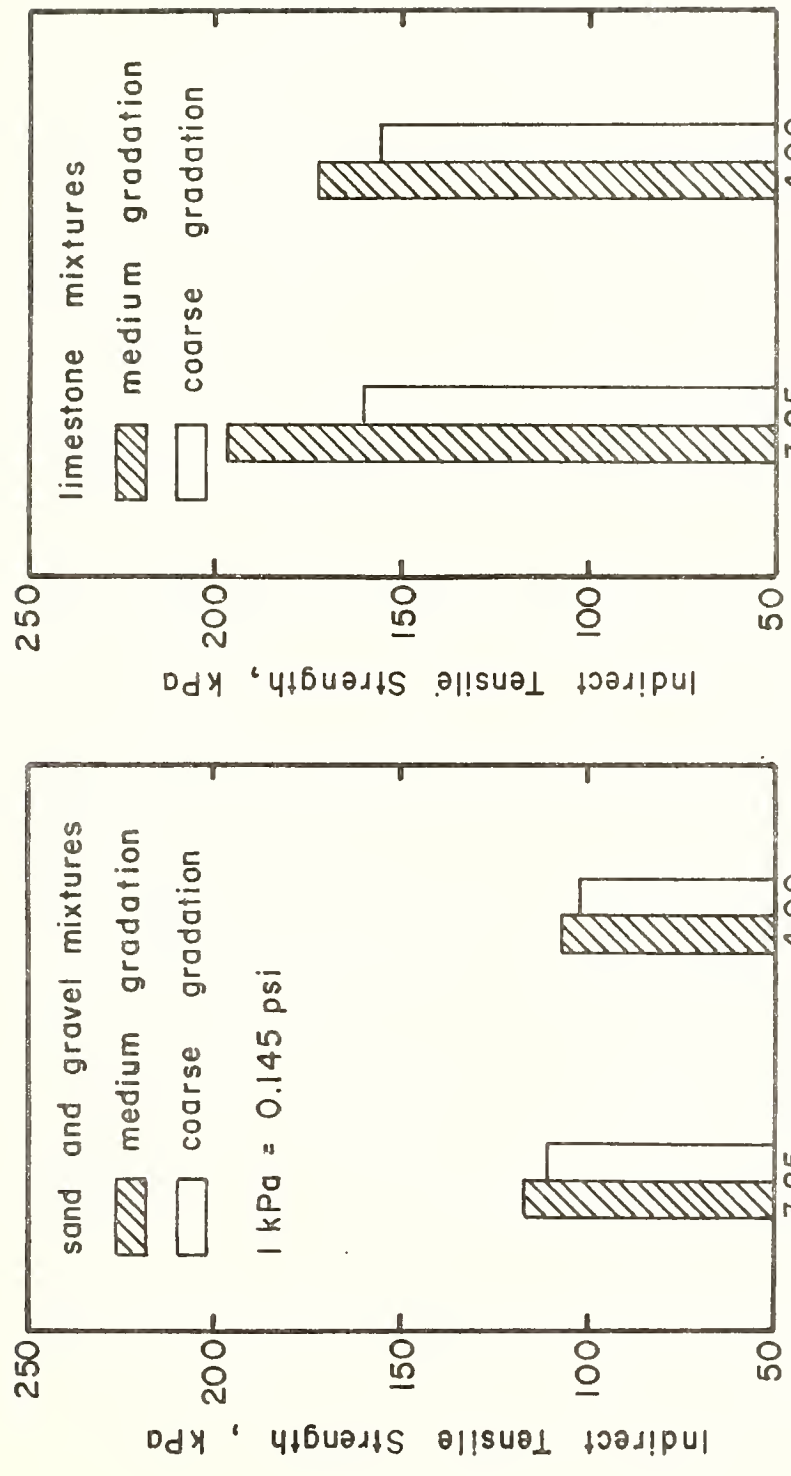


FIGURE 4.15, EFFECT OF AGGREGATE TYPE, AGGREGATE GRADATION AND ASPHALT EMULSION CONTENT ON THE INDIRECT TENSILE STRENGTH (4.5% W, oven curing and 24°C (75°F) test temperature)

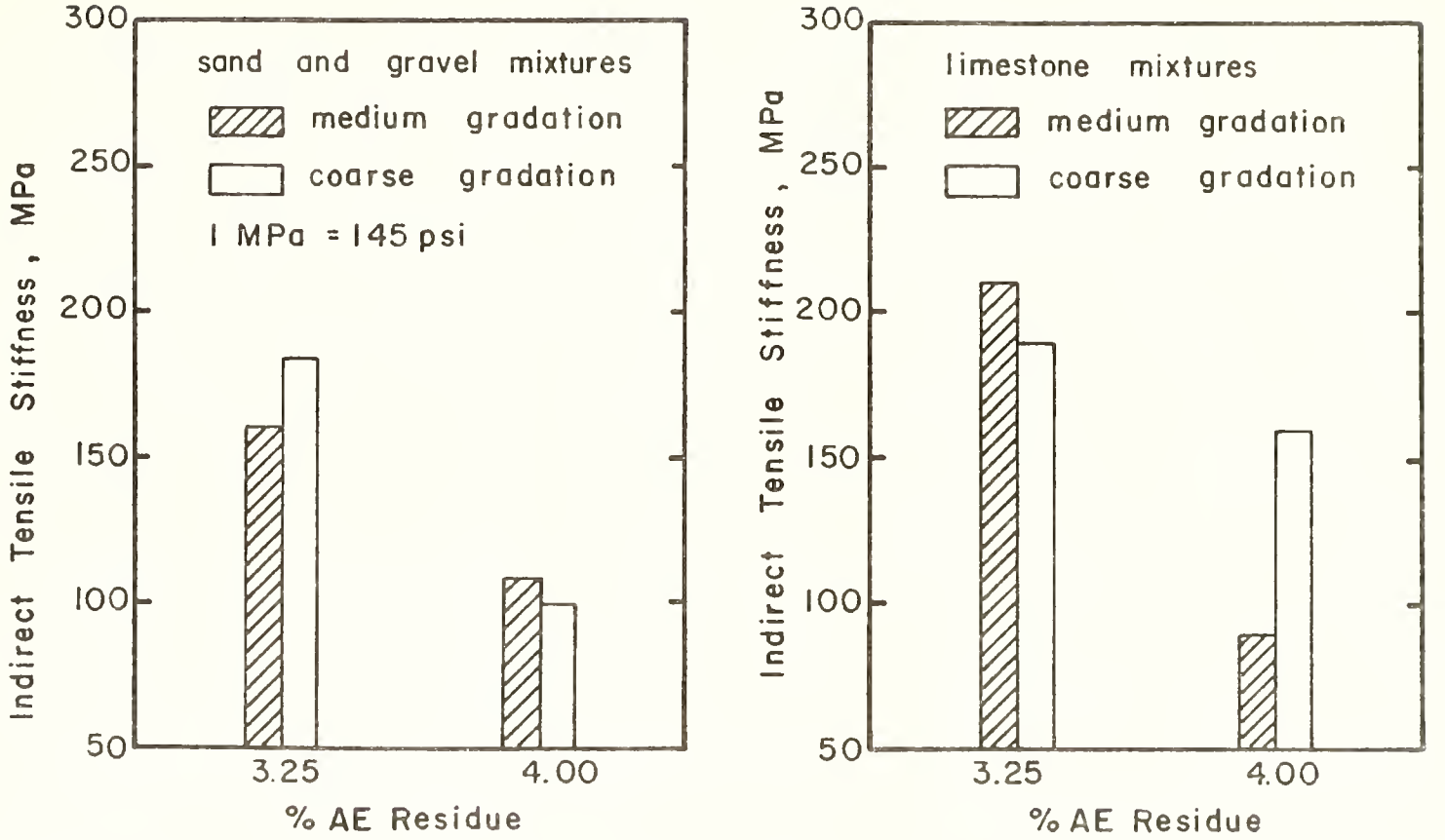


FIGURE 4.16, EFFECT OF AGGREGATE TYPE, AGGREGATE GRADATION AND ASPHALT EMULSION CONTENT ON THE INDIRECT TENSILE STIFFNESS (4.5% W, oven curing and 24°C(75°F) test temperature)

(150.4 pcf), while it was 2376 kg/m^3 (148.3 pcf) for the corresponding coarse graded specimens. The wet unit weight of the specimen at time of testing (after curing) was also larger for medium graded specimens than coarse graded specimens. The average wet unit weight at time of testing was 2377 and 2347 kg/m^3 (148.3 and 146.5 pcf) for medium and coarse graded specimens respectively. The average wet unit weight of the specimens for the different aggregate types, aggregate gradation and asphalt emulsion contents is shown in Figure 4.17. Meanwhile, the dry unit weight of the specimens took the same trend as the wet unit weight at time of testing. The average dry unit weight of medium graded specimens was 2361 kg/m^3 (147.3 pcf), while it was 2335 kg/m^3 (145.7 pcf) for the corresponding coarse graded specimens.

c. Air Voids

The amount of air voids was largely affected by aggregate gradation. Coarse graded specimens had a larger percent air voids than medium graded specimens. The average air voids for medium graded specimens was 6.66% of the total volume while it was 8.10% for the corresponding coarse graded specimens. The interaction effect of aggregate type, aggregate gradation and asphalt emulsion content on the amount of air voids is depicted in Figure 4.18. Larger percents of air voids were obtained for coarse graded mixtures than medium graded mixtures especially when limestone was used.

The amount of total voids, which is the sum of air voids and voids filled with moisture, displayed the same trend as the air voids for the different aggregate types, aggregate gradations and asphalt emulsion contents. Larger percents of the total voids were obtained for coarse

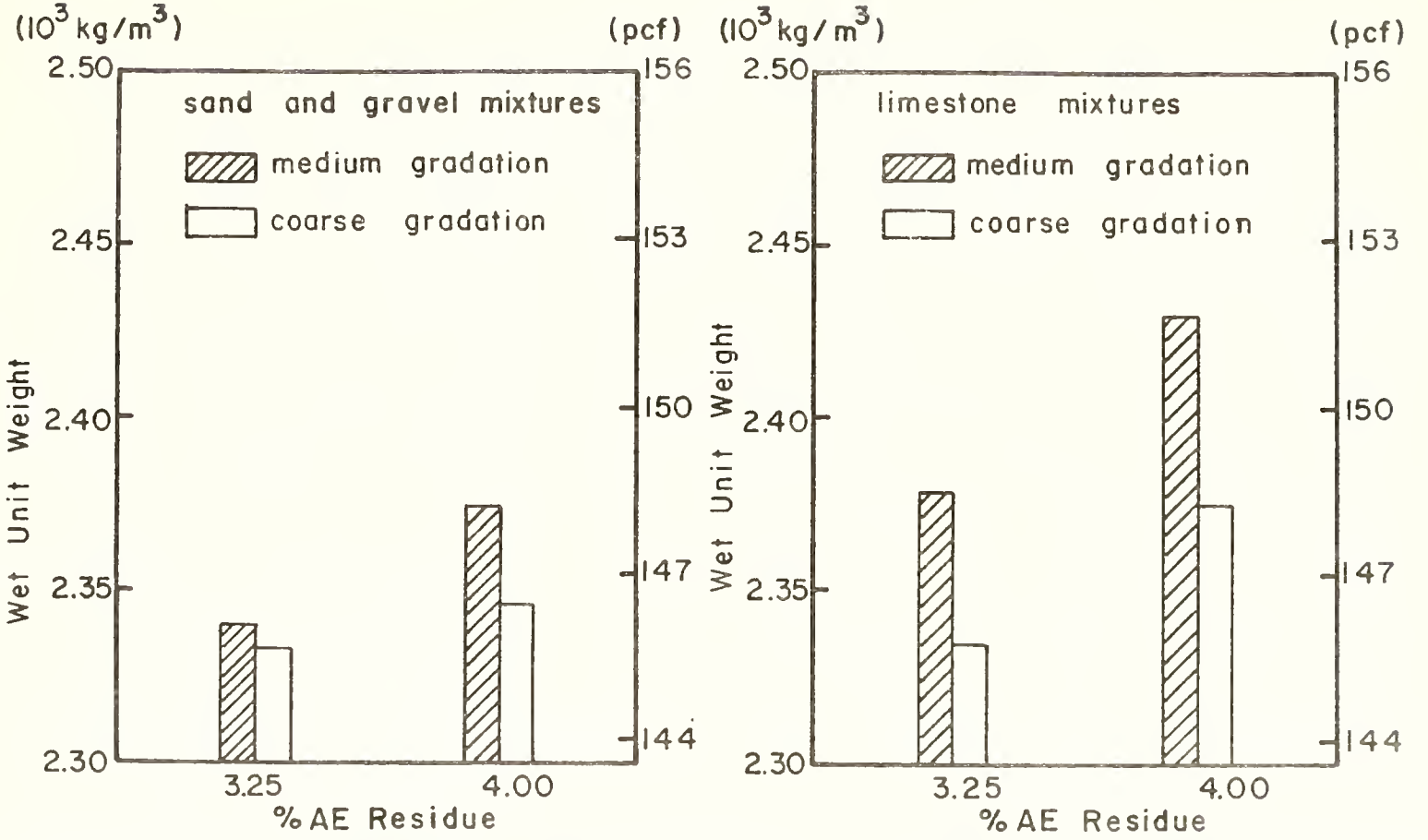


FIGURE 4.17, EFFECT OF AGGREGATE TYPE, AGGREGATE GRADATION AND ASPHALT EMULSION CONTENT ON THE WET UNIT WEIGHT AT TIME OF TESTING (4.5% W, oven curing and 24°C (75°F) test temperature)

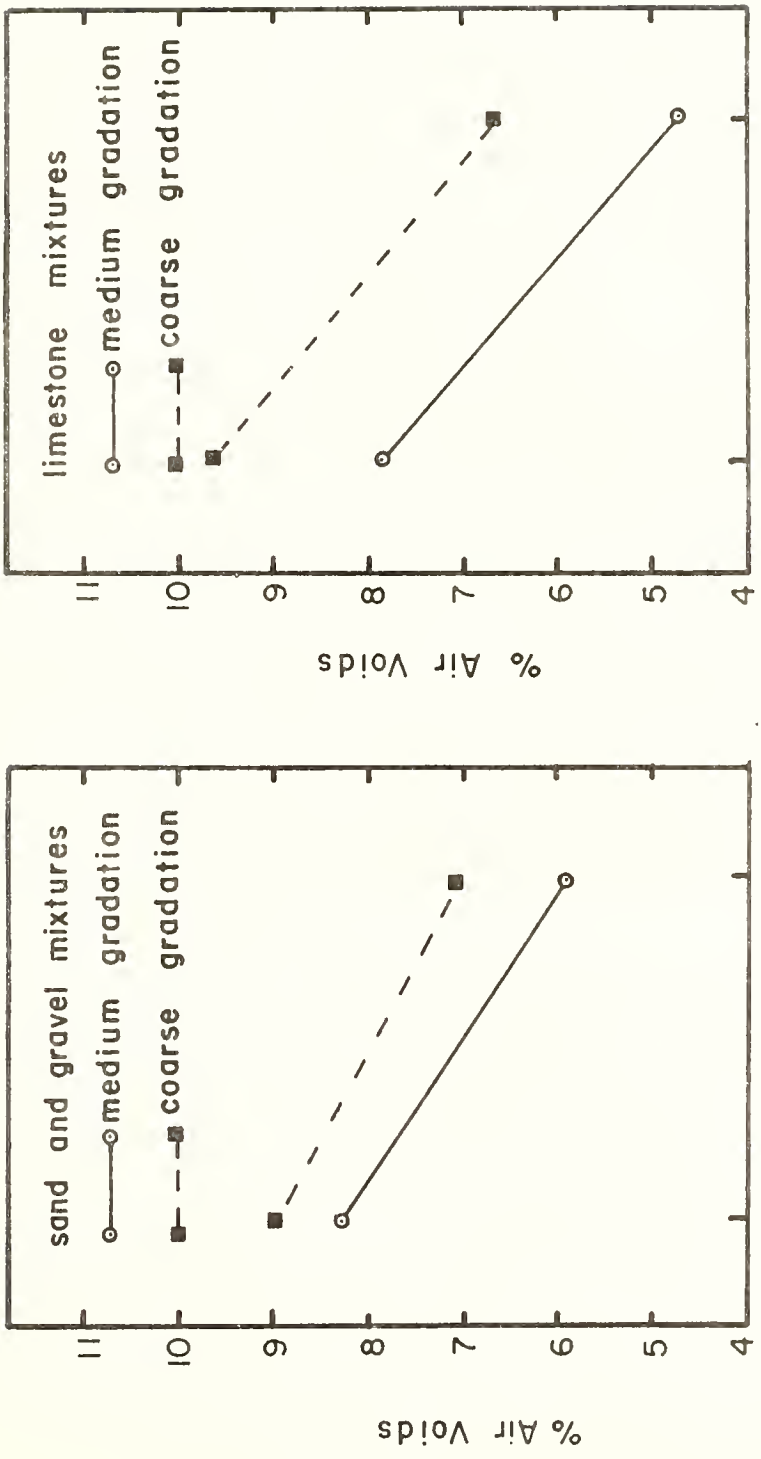


FIGURE 4.18, EFFECT OF AGGREGATE TYPE, AGGREGATE GRADATION AND ASPHALT EMULSION CONTENT ON AIR VOIDS AT TIME OF TESTING (4.5% W, oven curing and 24°C(75°F) test temperature)

graded specimens than medium graded specimens. The amounts of total voids for the different combinations of the different factors are presented in Table 4.3.

Table 4.3 Percent Total Voids for Different Aggregate Types, Aggregate Gradations and Asphalt Emulsion Contents

	Sand and Gravel		Limestone	
Asphalt Residue Content	Medium	Coarse	Medium	Coarse
3.25%	9.52	9.74	9.05	10.58
4.00%	7.33	8.30	6.89	8.26

The voids in the mineral aggregate, VMA, was affected by the aggregate gradation in a similar way as the air voids and the total voids. Larger values of VMA were obtained for coarse graded mixtures than medium graded mixtures. The average VMA for medium graded specimens was 16.38% of the total volume, while it was 17.31% for coarse graded specimens.

4.5 Water Sensitivity Test

The affect of water on the characteristics of the asphalt emulsion mixture was investigated using a modification of the Asphalt Institute water sensitivity test (5). This test was found to be an essential part in the characterization of the asphalt emulsion mixture. The test is not very harmful to specimens taking into consideration the low strength of the mixture at early ages. Also, the test allows a reasonable amount of moisture to be absorbed by the specimens. In this test, specimens were weighed after they had been cured for the required amount of time.

Specimens were subjected to a vacuum of 30 mm Hg for one hour (Figure 4.19). At the end of the one hour period, water was drawn into the vacuum chamber submerging the specimens at an ambient temperature of 22° C (72° F). The vacuum was released and the specimens were transferred to a water bath at the same temperature for 24 hours. The saturated surface dry weights of the specimens were then determined.

Upon completion of the water sensitivity test, the vacuum saturated specimens were placed in a constant temperature chamber of 24° C (75° F) for about 1/2-1 hour before performing the indirect tensile test. The test was conducted at 24° C (75° F) using the same equipment and experimental procedure discussed before which were used for the dry specimens. After conducting the indirect tensile test, the specimens were crushed and dried in a forced draft oven for 24 hours at 110° C (230° F) then weighed. The dry weight of the specimen represents the weight of the dry aggregate plus the asphalt residue weight.

Measurements that were determined from the test were as shown below. These measurements were important to indicate the effect of vacuum saturation on the mixture performance at different conditions.

1. Indirect tensile strength of the vacuum saturated specimens, as calculated using the maximum load which the specimen can resist (see Equation 4.1).
2. Indirect tensile stiffness of the vacuum saturated specimens which was obtained from the continuous recording of the load versus horizontal deformation of the specimens and assumed Poisson's ratio values of 0.35 at 24° C (75° F) (see Equation 4.3).
3. Indirect tensile index of the vacuum saturated specimens using the

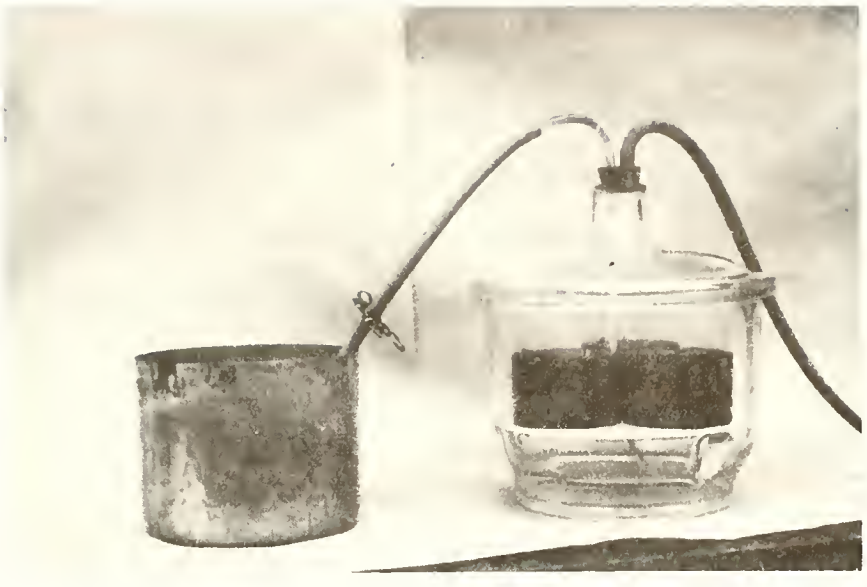


FIGURE 4.19, VACUUM SATURATION APPARATUS

same method which was used for the dry specimens.

4. Moisture contents of the specimens before and after vacuum saturation expressed as percents by weight of the dry aggregate.
5. Moisture absorption of the vacuum saturated specimens (moisture pick-up) as a percent by weight of the dry aggregate; which is the difference between moisture contents after and before vacuum saturation.
6. Total liquid of the vacuum saturated specimen as a percent by weight of the dry aggregate; which is the sum of asphalt residue content and water content after vacuum saturation.

The different factors which were evaluated in the water sensitivity test study were as follows: (See Table 4.1)

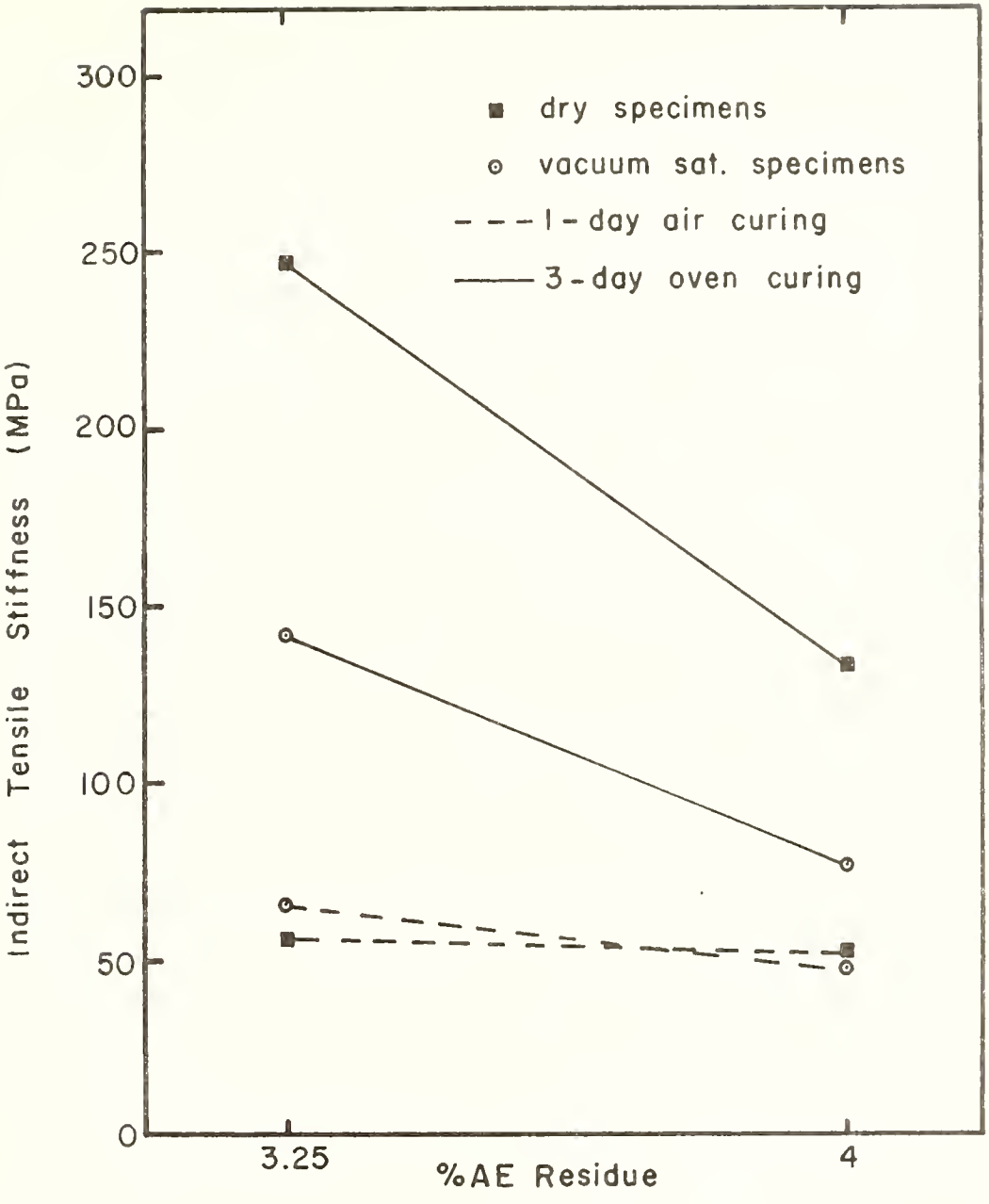
1. Aggregate type; both sand and gravel mixture and limestone were used.
2. Asphalt emulsion residue content; 3.25 and 4% by weight of the dry aggregate.
3. Curing; two levels of curing were considered which were 1-day air curing and 3-day oven curing at 49°C (120°F). These two curing levels represented the initial and long-term curing conditions of the asphalt emulsion mixture in the field.

One aggregate gradation was used in all vacuum saturated specimens which was the medium gradation, MG (Figure 3.1). The initial moisture added to the mixtures was 3% of the dry weight of aggregate. Three replicates for the different factor combinations were tested. A comparison between the indirect tensile test results of the corresponding dry and vacuum saturated specimens was performed.

According to the results obtained from the study, it was found that the indirect tensile stiffness of the oven cured specimens was affected more than the air cured specimens by vacuum saturation (Figure 4.20). For oven cured specimens, the indirect tensile stiffness of the dry specimens was larger than vacuum saturated specimens. However, for 1-day air cured specimens, the effect of vacuum saturation was not large. The reason for this effect was mainly due to the high amount of moisture absorbed by the oven cured specimens during vacuum saturation compared to air cured specimens. The average reduction in the indirect tensile stiffness due to vacuum saturation was 43% for oven cured specimens for both asphalt residue contents. Meanwhile the indirect tensile stiffness before and after vacuum saturation was not largely affected by aggregate type.

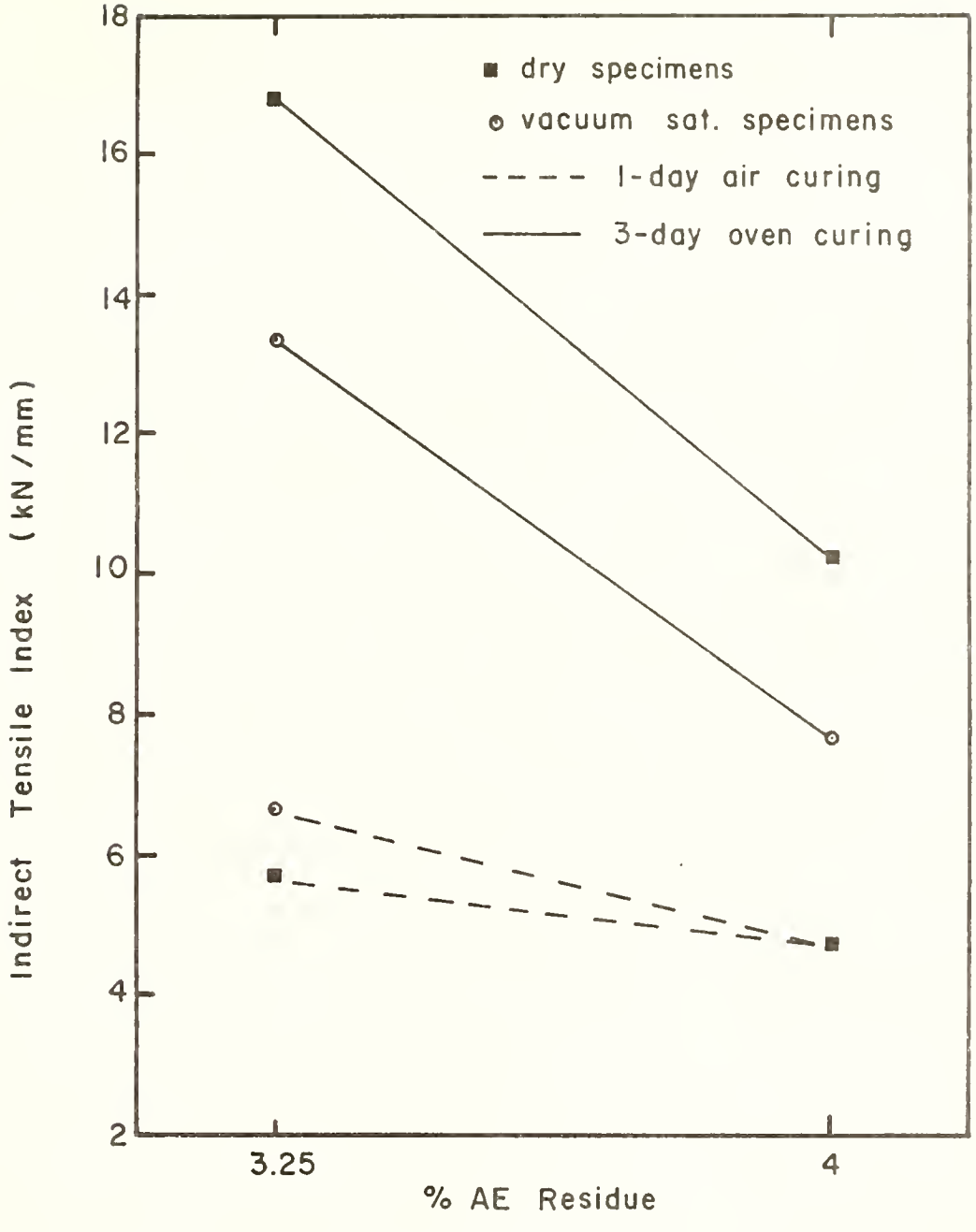
The indirect tensile strength of the vacuum saturated specimens was effected by the curing condition and aggregate type. Large indirect tensile strength values were obtained for oven cured limestone mixtures compared to air cured sand and gravel mixtures. The difference between the indirect tensile strengths before and after vacuum saturation was not large and it did not show a consistent trend. In addition, the total tensile strain at failure was not largely affected by vacuum saturation.

The indirect tensile index was affected by the vacuum saturation for oven cured specimens as shown in Figure 4.21. The average indirect tensile index decreased due to the vacuum saturation of oven-cured specimens for the different asphalt emulsion contents. At 1-day air curing, however, the average indirect tensile index was not largely af-



Note:
1 MPa = 145 psi

FIGURE 4.20, EFFECT OF VACUUM SATURATION ON THE INDIRECT TENSILE STIFFNESS FOR DIFFERENT ASPHALT EMULSION CONTENTS AND CURINGS (3% W and 24°C (75°F) test temperature)



Note: 1 kN/mm = 5.7×10^3 lb/in.

FIGURE 4.21, EFFECT OF VACUUM SATURATION ON THE INDIRECT TENSILE INDEX FOR DIFFERENT ASPHALT EMULSION CONTENTS AND CURINGS (3% W and 24°C (75°F) test temperature)

fected by vacuum saturation especially at 4% asphalt residue content. Moreover, in most cases, the indirect tensile index was large for limestone mixtures than for sand and gravel mixtures.

The amount of moisture absorbed by the mixture during vacuum saturation affects the performance of the mixture. When the amount of moisture absorbed during saturation increases, the stripping potential increases and the bond between asphalt residue and aggregate particles is weakened. The average values of moisture absorption due to vacuum saturation for the different asphalt emulsion contents, curing levels and aggregate types are demonstrated in Figure 4.22. Mixtures containing small amounts of asphalt residue had a higher percentage of air voids and consequently absorbed larger amounts of moisture during vacuum saturation than mixtures containing higher amounts of asphalt residue. Also, oven cured specimens had a higher percentage of air voids than air cured specimens. Therefore, larger amounts of moisture were absorbed by oven cured specimens than air cured specimens in most cases. In addition, limestone mixtures absorbed more moisture during vacuum saturation than sand and gravel mixtures for the same reason.

In general, the average amount of moisture absorption during vacuum saturation for all mixtures was 1.48% of the dry weight of aggregate. The amount of moisture absorption did not exceed 2.5% for any mixture used in the study. Moisture absorption had some influence on the tensile characteristics of the asphalt emulsion mixture. However, it did not result in serious damage or weakness in the mixture. The amount of moisture absorbed by the mixture during vacuum saturation was related to the amount of air voids. No correlation was obtained between the amount

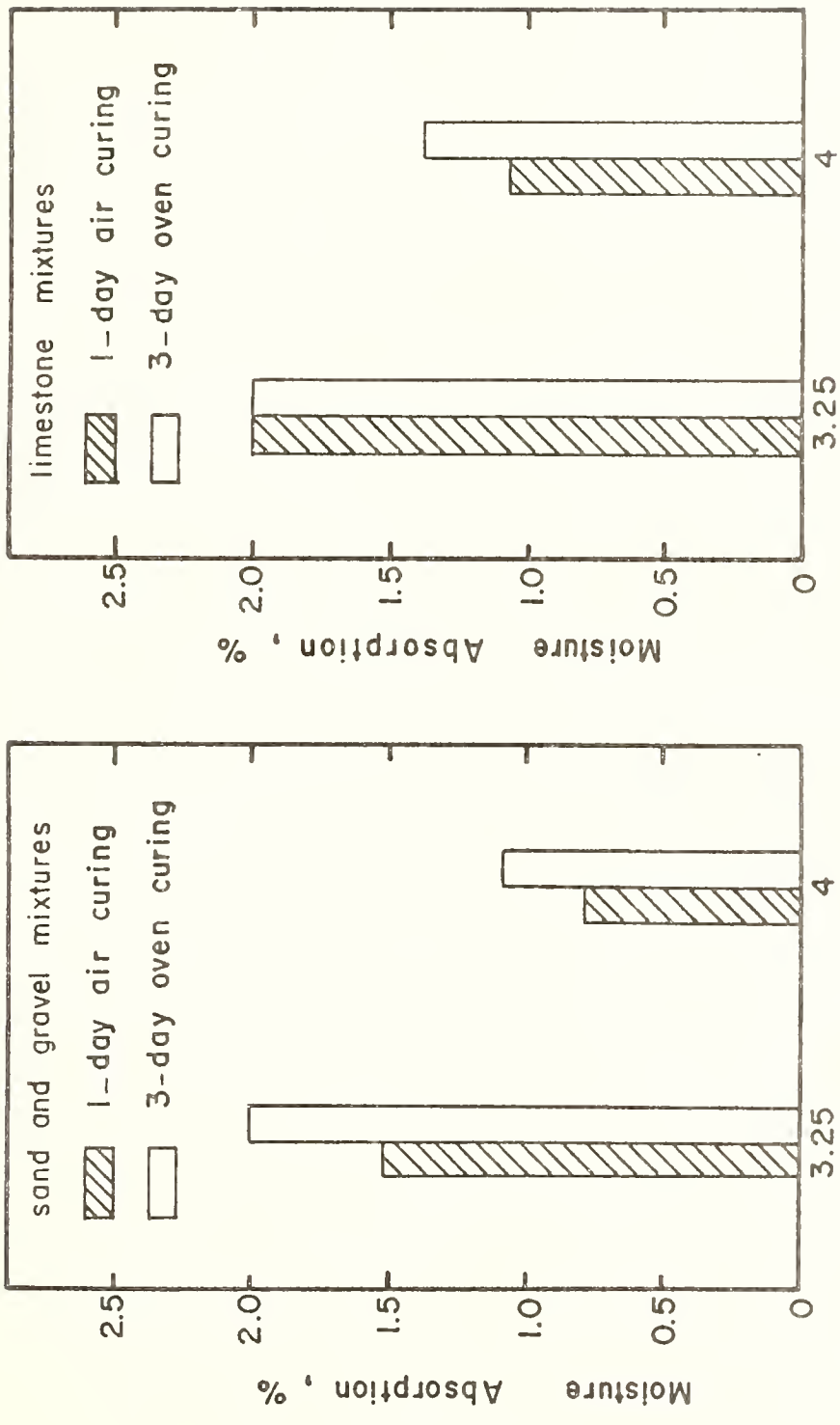


FIGURE 4.22, AVERAGE MOISTURE ABSORPTION DURING VACUUM SATURATION FOR DIFFERENT ASPHALT EMULSION CONTENTS, CURINGS AND AGGREGATE TYPES (3% initial added moisture)

of moisture absorption and the indirect tensile test results because of the small amount of moisture absorption in most cases.

The percent total liquid after vacuum saturation, which is the sum of asphalt residue content and moisture content, was affected by the curing level of the mixtures. The average total liquid of the vacuum saturated specimens decreased from 6.63% for 1-day air curing to 6.01% for 3-day oven curing. The corresponding averages for the same specimens before vacuum saturation were 5.29 and 4.94 for 1-day air curing and 3-day oven curing respectively. The amount of total liquid after vacuum saturation was affected also by the amount of asphalt residue in the mixture. Increasing the asphalt residue content from 3.25 to 4% increased the amount of total liquid from an average of 6.21 to 6.43% by weight of dry aggregate respectively.

4.6 Summary of Indirect Tensile Test Results

In this chapter, the performance of the asphalt emulsion mixture was investigated using the indirect tensile test. Different design parameters were evalutated under several mix variables and temperatures. Two aggregate types, aggregate gradations, asphalt emulsion contents, initial added moistures and curing levels were considered. One asphalt emulsion type and grade was utilized in the study. The test was performed at three different temperatures. A summary of the indirect tensile test results and other asphalt emulsion mixture properties is presented in Table 4.4 and Appendix C. The important findings of the study are as follows:

1. Test temperature was the most important factor that affected the indirect tensile properties of the mixture. High test temperatures

Table 4.4 Summary of the Indirect Tensile Test Results and Other AEM Properties

Measurement	Range	Important Factors
Strength	25-596 kPa (3.6-86 psi)	T,AG,C,W
Poisson's Ratio	*	T,C
Stiffness	17-2482 MPa (2.4-360 ksi)	T,AE,AG
Failure Strain	5.8×10^{-3} - 11.9×10^{-3} mm/mm (in./in.)	AE,C,T
Index	0.8 - 119 kN/mm (4.5×10^{3}-680×10^{3} lb/in)	T,AG,AE
CM	2348-2466 kg/m3 (147.3-152.8 pcf)	AE, W, AG
γ_w	2312-2450 kg/m^3 (144.3-152.8 pcf)	AE, C, AG
γ_d	2301-2424 kg/m^3 (143.6-151.3 pcf)	AE, AG
%WC	0.25 - 2.20%	AE, C
%TL	3.50 - 5.97%	AE, C
$\%V_A$	2.560 - 9.800%	AE, C
$\%V_T$	5.803 - 10.509%	AE
%VMA	14.997 - 17.680%	--

Note: The effect of aggregate gradation is not included in this table.

*Unreasonable Poisson's ratio values were obtained.

increased Poisson's ratio and decreased the indirect tensile strength, stiffness and index. Test temperature also had some influence on the total tensile strain at failure.

2. Limestone mixtures had higher indirect tensile strengths and indices than did the sand and gravel mixtures. Aggregate type had a significant effect on the indirect tensile stiffness specially at low temperature. In addition, limestone mixtures had higher unit weights than sand and gravel mixtures.
3. In most cases increasing the asphalt emulsion content decreased the indirect tensile stiffness and index. It also increased the total tensile strain at failure, unit weight at time of compaction, retained moisture and unit weight at time of testing. Both air voids and total voids at time of testing decreased when the asphalt emulsion content increased.
4. The characteristics of the mix changed markedly when the air curing condition was compared to the oven curing condition. Oven curing increased the indirect tensile strength of the mixture and decreased Poisson's ratio and total strain at failure. Oven curing also decreased the wet unit weight and moisture retained at time of testing. It increased the air voids in the mixture as well.
5. Increasing the initial added moisture from 3% to 4.5% of the dry weight of aggregate decreased the indirect tensile strength of the mix. At the same time, the high initial moisture added to the mixture resulted in high unit weights of the mixture at time of compaction.
6. The indirect tensile index proved to have a good correlation with

asphalt emulsion content, and test temperature. It is believed that using the indirect tensile index together with other indirect tensile parameters would provide a good characterization of the asphalt emulsion mixture.

7. Medium graded mixtures gave higher indirect tensile strengths, total tensile strains at failure, unit weights and less voids than coarse graded mixtures.

8. Vacuum saturation reduced the indirect tensile stiffness and index for oven cured specimens, but did not have a large effect on the indirect tensile strength of the mixture. The moisture absorption during vacuum saturation was related to the amount of air voids in the mixture. It did not exceed 2.5% by weight of dry aggregate and it did not cause any serious damage or weakness to the asphalt emulsion mixture.

CHAPTER 5

RESILIENT MODULUS TEST

5.1 Introduction

As traffic moves on the pavement, the vertical and horizontal stresses change such that each wheel pass can be considered as a stress pulse. The magnitude, shape and duration of these pulses vary with the wheel load, its speed, and the depth in the pavement at which the stress is considered (56). Therefore, the use of the dynamic tests is the most realistic method to simulate the actual stress conditions of the pavement. The resilient characteristics obtained by the dynamic load tests were found to be very important in highway pavement evaluation.

One of the common dynamic tests frequently used to determine the resilient characteristics of the pavement material mixtures is the method of diametral loading. The test is conducted by applying a light pulsating load across the vertical diameter of the specimen and recording the vertical and horizontal deformations during the load application. Poisson's ratio and the resilient modulus values can both be determined from the test. These values are necessary for the multilayer elastic design method as well as the finite element method of pavement design (9,46) and are valuable for the characterization of pavement material mixtures.

In this part of the study, the diametral resilient modulus test was used to evaluate the asphalt emulsion mixes performance. The instan-

taneous resiliet Poisson's ratio and resilient modulus were determined at different mix components and environmental conditions. The effect of vacuum saturation on the dynamic characteristics of the mixture was also evaluated. In addition, the relationship between the dynamic characteristics and the indirect tensile properties of the mixture was investigated.

5.2 Design of Experiment

The Analysis of Variance (ANOVA) tests were performed to determine the effect of some independent variables (factors) on the response variables of the asphalt emulsion mixtures. The response variables and the independent variables are shown below.

5.2.1 Response Variables

Some of the response variables were measured to give indications of the resilient characteristics of the asphalt emulsion mixes, while others concerned the physical properties of the mixtures. The response variables which were considered in this part of the study were as follows:

1. Instantaneous resilient Poisson's ratio as determined by measuring the instantaneous resilient vertical and horizontal deformations of the specimen when the pulsating load was applied (see Equation 5.2).
2. Instantaneous resilient modulus, which was calculated using the previously determined instantaneous resilient Poisson's ratio value and the instantaneous resilient horizontal deformation of the specimen when the pulsating load was applied (see Equation 5.3).
3. Unit weight after compaction; which is a measure of compatability of

the mixture. It was determined by obtaining the specimen weight and height just after compaction while the specimen was still in the mold.

4. Wet and dry unit weights at time of testing. The wet unit weight referred to the density of the specimen after curing including the moisture portion, while the dry unit weight was determined excluding the moisture portion in the mixture.
5. Moisture retained in the specimen at time of testing (after curing), as a percent by weight of the dry aggregate.
6. Total liquid in the mixture at time of testing as a percent of the dry weight of aggregate; which in the sum of percent of asphalt residue and percent of moisture retained after curing.
7. Voids at time of testing (after curing) including:
   a. Air voids in the compacted asphalt emulsion moisture.
   b. Total voids; which are the sum of air voids and voids filled with moisture in the compacted mixture.
   c. Voids in the mineral aggregate, VMA; which are defined as the intergranular void spaces between the aggregate particles in the compacted asphalt emulsion mixture.

Voids were expressed as percents of the total volume of the compacted specimen. They were determined on the bases of the apparent specific gravity of the aggregate and assuming no asphalt was absorbed into the aggregate. (For voids calculations, see Appendix A).

5.2.2 Independent Variables (Factors)

The independent variables considered in this investigation are presented in Table 5.1. These variables are as follows:

1. Aggregate type, AG; two types of aggregate were considered. The first type was a mixture of sand and gravel, while the second type was a crushed limestone as discussed in Chapter 3.
2. Aggregate gradation, G; two aggregate gradations were used. The two gradations were medium gradation (MG) and coarse gradation (CG) as shown in Figure 3.1.
3. Asphalt emulsion residue content, AE. Two levels of asphalt residue contents were used; 3.25 and 4% of the dry weight of aggregate. These levels of asphalt residue contents were chosen within the range recommended by ISHC standard specifications.
4. Initial added moisture, W. Three levels of initial added moisture were used; 1.5, 3 and 4.5% of the dry weight of aggregate. This range of mixing water provided a reasonable coating of asphalt residue on the aggregate particles.
5. Curing, C; three curing levels were evaluated as shown below:
   a. One-day air curing at a room temperature of 22°C (72°F).
   b. Three-day air curing at a room temperature of 22°C (72°F).
   c. Three-day oven curing at 49°C (120°F). These curing levels represented the initial (after construction), intermediate and long-term curing conditions in the field respectively.
6. Test temperature, T; three temperature levels were used in the resilient modulus test. These temperatures were 10, 24, and 38°C (50, 75, and 100°F) respectively.

TABLE 5.1, RESILIENT MODULUS TEST VARIABLES

Curing	Test Temp.	% Added Moisture	% AE Residue	Gradation	Aggregate	Sand & Gravel				Limestone			
						MG		CG		MG		CG	
						3.25	4	3.25	4	3.25	4	3.25	4
1-day Air Curing	10 C (50 F)	1.5				X	X	X	X	X	X	X	X
		3				X	X	X	X	X	X	X	X
		4.5				X	X	X	X	X	X	X	X
	24 C (75 F)	1.5				X	X	X	X	X	X	X	X
		3				⊗	⊗	X	X	⊗	⊗	X	X
		4.5				X	X	X	X	X	X	X	X
3-day Air Curing	10 C (50 F)	1.5				X	X	X	X	X	X	X	X
		3				X	X	X	X	X	X	X	X
		4.5				X	X	X	X	X	X	X	X
	24 C (75 F)	1.5				X	X	X	X	X	X	X	X
		3				X	X	X	X	X	X	X	X
		4.5				X	X	X	X	X	X	X	X
	38 C (100 F)	1.5				X	X	X	X	X	X	X	X
		3				X	X	X	X	X	X	X	X
		4.5				X	X	X	X	X	X	X	X
3-day Oven Curing	10 C (50 F)	1.5				X	X	X	X	X	X	X	X
		3				X	X	X	X	X	X	X	X
		4.5				X	X	X	X	X	X	X	X
	24 C (75 F)	1.5				X	X	X	X	X	X	X	X
		3				⊗	⊗	X	X	⊗	⊗	X	X
		4.5				X	X	X	X	X	X	X	X
	38 C (100 F)	1.5				X	X	X	X	X	X	X	X
		3				X	X	X	X	X	X	X	X
		4.5				X	X	X	X	X	X	X	X

Note:

X : dry test ⊗ : water sensitivity test

Three replicates for each combination of factors were tested. At one-day air curing, however, specimens were not firm enough to be tested at 38°C (100°F). Therefore, factor combinations of one-day air curing and 38°C (100°F) test temperature were dropped from the analysis. The total number of data points were 576 representing all other factor combinations (see Table 5.1).

5.2.3 Statistical Models

The ANOVA tests were used to determine the significant effects of the different factors and interactions on the response variables. Two basic statistical models were used in the ANOVA. The first model included all three curing levels and two levels of test temperature which were 10 and 24°C (50 and 75°F). The second model included two curing levels (3-day air curing and 3-day oven curing) and all three levels of test temperature. The two statistical models took the same general form except that levels of variables C and T were different as follows:

$$y_{ijk\ell m} = \mu + R_i + \delta_{(i)} + M_j + RM_{ij} + \gamma_{(ij)}$$

$$+ W_k + RW_{ik} + MW_{jk} + RMW_{ijk} + \omega_{(ijk)}$$

$$+ C_\ell + RC_{i\ell} + MC_{j\ell} + \ldots + \eta_{(ijk\ell)}$$

$$+ T_m + \ldots + \varepsilon_{(ijk\ell m)}$$

where

$y_{ijk\ell m}$ = measured response variable (Poisson's ratio, resilient modulus, ... etc.)

μ = overall mean

R_i = effect of replicates

M_j = AG + G + AE + interactions

AG = effect of aggregate type

G = effect of aggregate gradation

AE = effect of asphalt emulsion residue content

W_k = effect of initial added moisture content

C_ℓ = effect of curing

T_m = effect of test temperature

$\delta_{(i)}, \gamma_{(ij)}, \omega_{(ijk)}$ and $\eta_{(ijk\ell)}$ = restrictions on randomization (2)

$\varepsilon_{(ijk\ell m)}$ = experimental error

All main effects were fixed except R was random. The subscripts assumed values:

$i = 1,2,3$

$j = 1,2$

$k = 1,2,3$

$\ell = 1,2,3$ (for the first model) and $1,2$ (for the second model)

$m = 1,2$ (for the first model) and $1,2,3$ (for the second model)

The statistical models followed the split plot design (2). According to these models, one replicate (R) for all combinations was performed first. The second replicate was performed next then the third replicate. Within each replicate, tests were performed on specimens having a certain curing level (C) before considering the other curing levels. Also, for every curing level, specimens were tested at a certain temperature (T) before testing at other temperatures. In addition, within each curing and temperature combination, specimens containing a

certain initial added moisture content (W) were tested before considering other levels of moisture contents. Tests were randomized for the different aggregate types (AG), aggregate gradations (G) and asphalt emulsion contents (AE) within each replicate, curing, temperature and initial added moisture combination. All factors and interactions were tested versus their interactions with the replicate (R) (see Appendix B). This method of design allows tests for all factors and interactions despite the restrictions on randomization. A level of significance of 5% was used in the different ANOVA tests.

In addition to these two statistical models, a third model was used to check the results. In this model, levels of curing were combined with temperature levels forming a new hypothetical factor with eight levels. Student Newman-Kule analysis was used to determine the significant effects of the individual levels of factors and interactions. The means of the response variables in each combination of factors (cell) were used in observing any physical trends that might be present. Finally, subjective judgements on the performance of AEM were made.

5.3 Equipment and Experimental Procedure

5.3.1 Equipment

The resilient modulus equipment (Figure 5.1) was similar to the equipment developed by Schmidt (51) with some modifications. It consisted mainly of a compressed air resource, solenoid valve, piston, loading frame, measuring devices and a two-channel chart recorder. The laboratory was equipped with a compressed air source which could be controlled by a pressure regulator. A solenoid valve activated by an electric circuit was used to provide pulses of compressed air. Those pulses

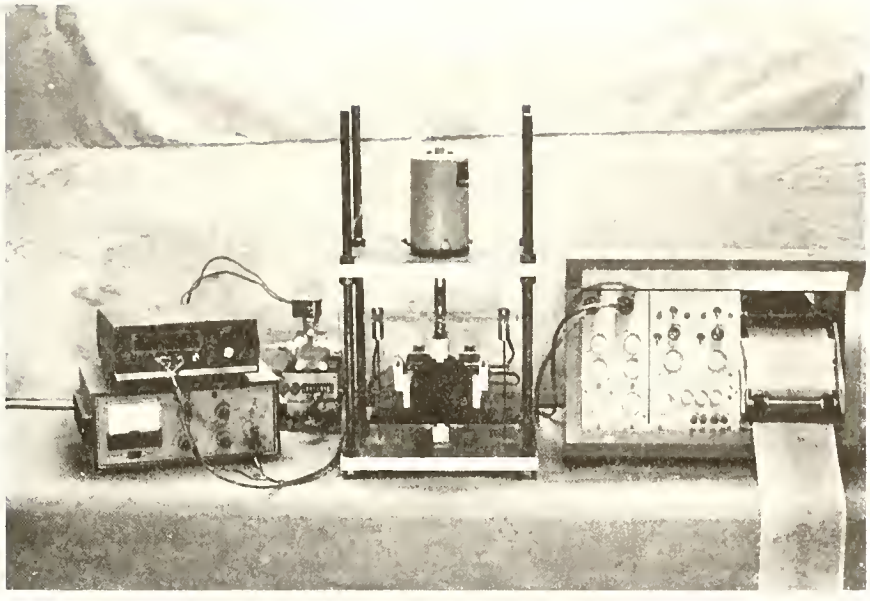


FIGURE 5.1, DIAMETRAL RESILIENT MODULUS MACHINE

of compressed air were transmitted to a light pulsating load by means of the piston fixed on top of the loading frame.

The load pulses were applied every 3 seconds with a dwell time of 0.1 second. The magnitude of the load was controlled by adjusting the compressed air using the pressure regulator. A constant load of 334 N (75 lb.) was used throughout the experiment. This load was chosen to avoid any damage to the specimen and at the same time to provide suitable values of vertical and horizontal deformations (15,50). The load was applied across the vertical diameter of the specimen using two curved stainless steel loading strips with 12.7 mm (1/2 in.) width. The loading strips were curved at the interface with the specimen with a radius of 51 mm (2 in.).

The vertical deformations of the specimen were measured using two identical Linear Variable Differential Transformers (LVDTs), fixed in a vertical position connecting the piston with the bottom base of the frame as may be seen in Figure 5.1. The two LVDTs were fixed at equal distances from the specimen on both sides. The output voltages of the two LVDTs were connected in series to obtain one output representing the sum of the two voltages. The output voltage was connected to one channel of the strip chart recorder.

The horizontal deformations, however, were measured using the same diametral extensometer which was used in the indirect tensile test. Details of the diametral extensometer are discussed in Section 4.3.1 of Chapter 4 (Figure 4.4). The output voltage of the horizontal LVDT, which was fixed to the diametral extensometer, was calibrated and connected to the other channel of the strip chart recorder. Meanwhile, the

diametral extensometer was fixed to a separate base behind the loading frame to reduce vibrations that might develop during the load application. The outputs of the LVDTs were calibrated using a micrometer and a voltmeter at temperatures of 10, 24, and 38°C (50, 75, and 100°F) which were used in the experiment.

5.3.2 Temperature Control

The experiment was conducted inside a large controlled temperature room. A thermometer was buried inside a dummy specimen to indicate the actual temperature of the specimens. It took between 2-4 hours to change the temperature to the required test temperature. During this period, specimens were kept in sealed plastic bags to reduce the moisture loss from the mixture. Also, coating the specimen with zinc stearate when the unit weights were determined helped in retaining moisture in the specimens.

5.3.3 Test Procedure

The following is a brief description of the testing procedure that was followed for the resilient modulus test.

1. When the specimen reached the required test temperature, it was removed from the plastic bag and placed in the resilient modulus test machine. The distance between the two loading strips was adjusted so that they touched the specimen before the load was applied. Care was taken to make sure that the specimen was exactly centered between the two loading strips.
2. The output voltages of the horizontal and vertical LVDTs were controlled by changing the position of the LVDTs' cores relative to the

coils in order that the LVDTs be used within the linear range.

3. A pulse load of 334 N (75 lb.) was then applied across the vertical diameter of the specimen every 3 seconds with a duration of 0.1 second.
4. During the load application, the changes in the output voltages of the LVDTs were converted to movements of the recording pens. The sensitivites of the recorder channels and the positions of the pens were adjusted to obtain readout recordings within the chart. The speed of the chart movement was adjusted to 5 mm/sec (0.2 in./sec).
5. The pulsating load was applied several times to the specimen before the results were considered. When constant vertical and horizontal deformations were obtained on the chart for at least 10 times, the load was stopped. This condition, however, was not fulfilled in all cases especially at high temperatures and/or low curing levels because of the tension cracks that were quickly formed in the specimen.
6. The specimen was rotated 90° and tested again in the new position using the same steps mentioned before. If large differences were found between deformation values for the two positions, the specimen was tested at a third position and the unreasonable results were discarded.
7. After the test was completed, specimens were crushed into small pieces and dried in a forced draft oven for 24 hours at 110°C (230°F). The weight of the dry material was determined which was the weight of the dry aggregate and the asphalt residue. This weight was used to determine the dry unit weight and the moisture

retained in the specimen as shown in Appendix A.

One of the advantages of the resilient modulus test is that it is a nondestructive type test. Therefore, some specimens were tested twice or three times at different temperatures. In this case, they were tested at the low temperatures first then at high temperatures to reduce damage or permanent deformations. Specimens were kept in sealed plastic bags while changing their temperatures between the different tests in order to reduce the moisture loss. When cracks or noticeable deformations occurred to the specimen, no further tests were performed on the same specimen.

5.4 Analysis of Results

When the pulsating load was applied across the vertical diameter of the specimen, a typical trace of the vertical and horizontal deformations was obtained as shown in Figure 5.2. The load pattern is also displayed in the figure. When a single repetition of load is applied, the corresponding vertical and horizontal deformations consist of the following components:

1. An instantaneous elastic deformation which is a function of the mix properties, temperature and the magnitude of the applied load.
2. A time-dependent response which is a function of all variables as before plus the duration of the applied load.
3. An instantaneous elastic rebound takes place when the load is removed which is a function of all variables mentioned under 1.
4. A time dependent recovered deformation which is a function of all

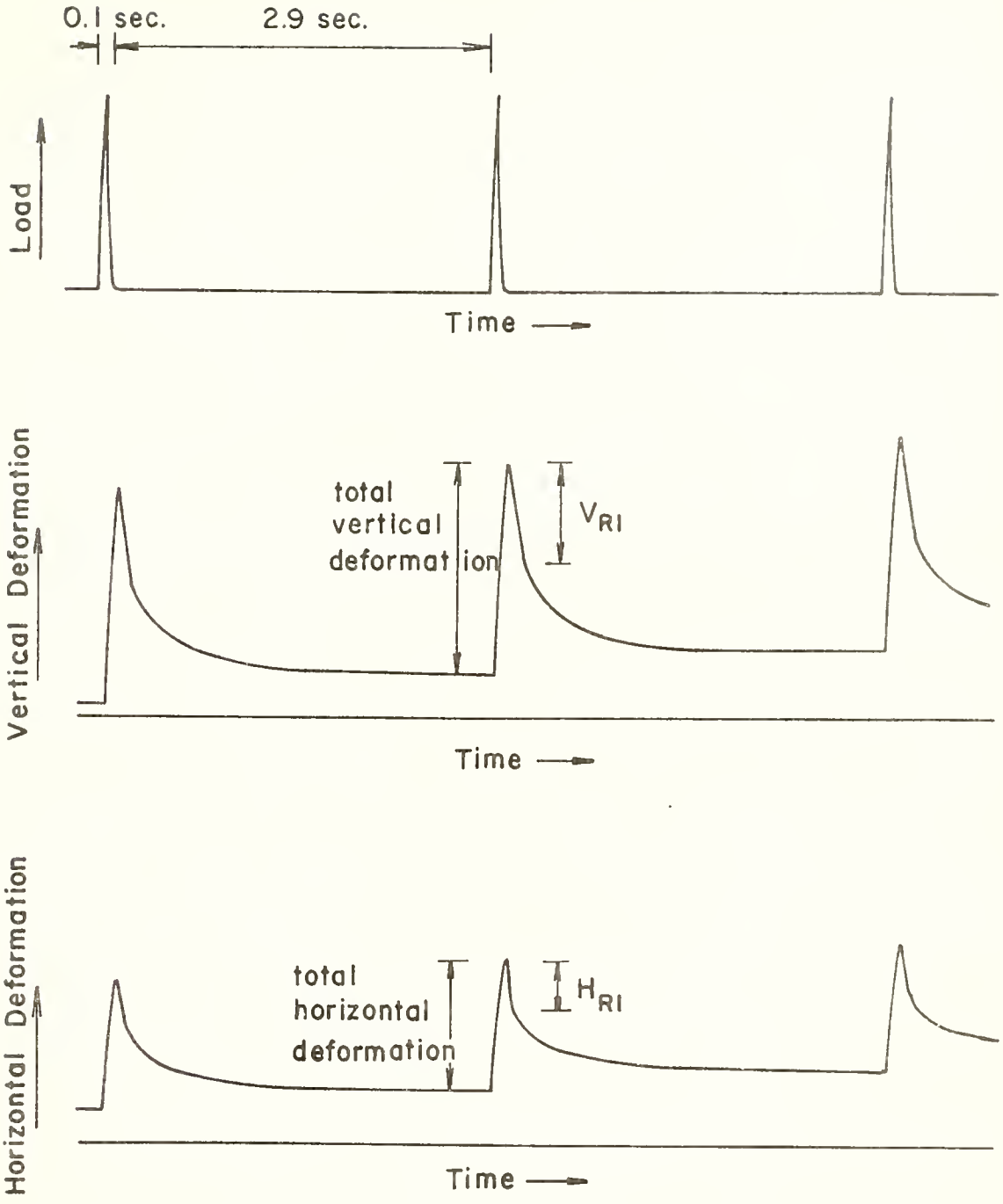


FIGURE 5.2, TYPICAL LOAD, VERTICAL DEFORMATION AND HORIZONTAL DEFORMATION VERSUS TIME IN THE RESILIENT MODULUS TEST

variables mentioned above plus the rebound time.

5. A small part of the total deformation that is not recoverable.

The resilient characteristics of the asphalt emulsion mixtures were determined for each specimen at the two testing positions and the average values of both positions were determined. Equations which were used to determine the indirect tensile stress, the instantaneous resilient Poisson's ratio and the instantaneous resilient modulus are shown below (34,37). These equations are valid only for the English units and are restricted to 102 mm (4 in.) diameter specimens with curved loading strips of 12.7 mm (1/2 in.) width. If the SI units are used, constants should be changed in the equations.

$$\sigma_{IT} = 0.156 \frac{P}{h} \tag{5.1}$$

$$\nu = 3.59 \frac{H_{RI}}{V_{RI}} - 0.27 \tag{5.2}$$

$$M_R = \frac{P(\nu + 0.27)}{h\, H_{RI}} \tag{5.3}$$

where

σ_{IT} = indirect tensile stress, psi

ν = instantaneous resilient Poisson's ratio

M_R = instantaneous resilient modulus, psi

H_{RI} = instantaneous resilient horizontal deformation, in.

V_{RI} = instantaneous resilient vertical deformation, in.

P = repeated load, lb

h = specimen height, in.

The indirect tensile stress is a function of the magnitude of the repeated load and specimen height (Equation 5.1). For a constant-magnitude repeated load, the stress changes only with the specimen height. Since the variation in the specimens' heights was small, the indirect tensile stresses had a small range from 30.2 kPa (4.38 psi) to 33.3 kPa (4.83 psi) with an average of 31.5 kPa (4.57 psi) for all specimens in the study. Meanwhile, the instantaneous resilient vertical deformations ranged from 0.015 to 0.076 mm (600 to 3000 microinches), while the instantaneous resilient horizontal deformations ranged from 0.0005 to 0.02 mm (20 to 800 microinches).

A study of each one of the response variables of the asphalt emulsion mixtures is discussed in the following sections of this chapter. This will be followed by a presentation of the water sensitivity test analysis corresponding to this phase of the study.

5.4.1 Instantaneous Resilient Modulus (M_R)

The resilient modulus is defined as the ratio of the applied stress to the recoverable or resilient strain when the load is applied in a dynamic condition. The instantaneous resilient modulus, M_R, obtained by the diametral repeated load test is analogous to the modulus of elasticity, E, determined from the static load test. In the diametral repeated load test, the M_R value is obtained using Equation 5.3.

At low temperatures, shrinkage cracks tend to develop in the pavement. The smaller the resilient modulus of the asphalt mixture, the lower the thermal stresses developed in the pavement by temperature changes. Thus, low resilient modulus values for asphalt treated mixtures are desired in order to obtain good performance at low tempera-

tures so that such cracks will be reduced or eliminated. On the other hand, high resilient modulus values are needed at high temperatures to reduce excessive deformation or rutting in the asphalt pavement due to the traffic loads. In general, asphaltic mixes which are not largely affected by temperature are required in order to have small variation in the resilient modulus values at different temperatures.

The instantaneous resilient modulus was found to be a good measure for asphalt emulsion mixture characterization. In this study the value of the resilient modulus was determined for different mixture components, curing levels and test temperatures. The M_R values of the individual specimens ranged from 212 MPa (30.7 ksi) to 1157 MPa (167.8 ksi) with an average of 531.9 MPa (77.2 ksi). According to the ANOVA results, the M_R value was largely affected by test temperature, curing and aggregate type. The effect of test temperature and curing on the average M_R value is demonstrated in Figure 5.3. It is obvious that increasing the test temperature had a large effect on decreasing the M_R value of the mixture for the same curing level. High temperatures decreased the viscosity of the asphalt residue and reduced the stiffness of the mixture. Therefore, the M_R obtained at high temperatures were smaller than values obtained at low temperatures. A reduction of about 55% occurred in the average value of M_R by increasing the test temperature from 10°C to 38°C (50 to 100°F) for both 3-day air and oven cured specimens.

It was found also that curing increased the M_R value of the mixtures for the same test temperature. A stiff mixture is obtained when curing was accomplished in the oven as compared to an air cured mixture.

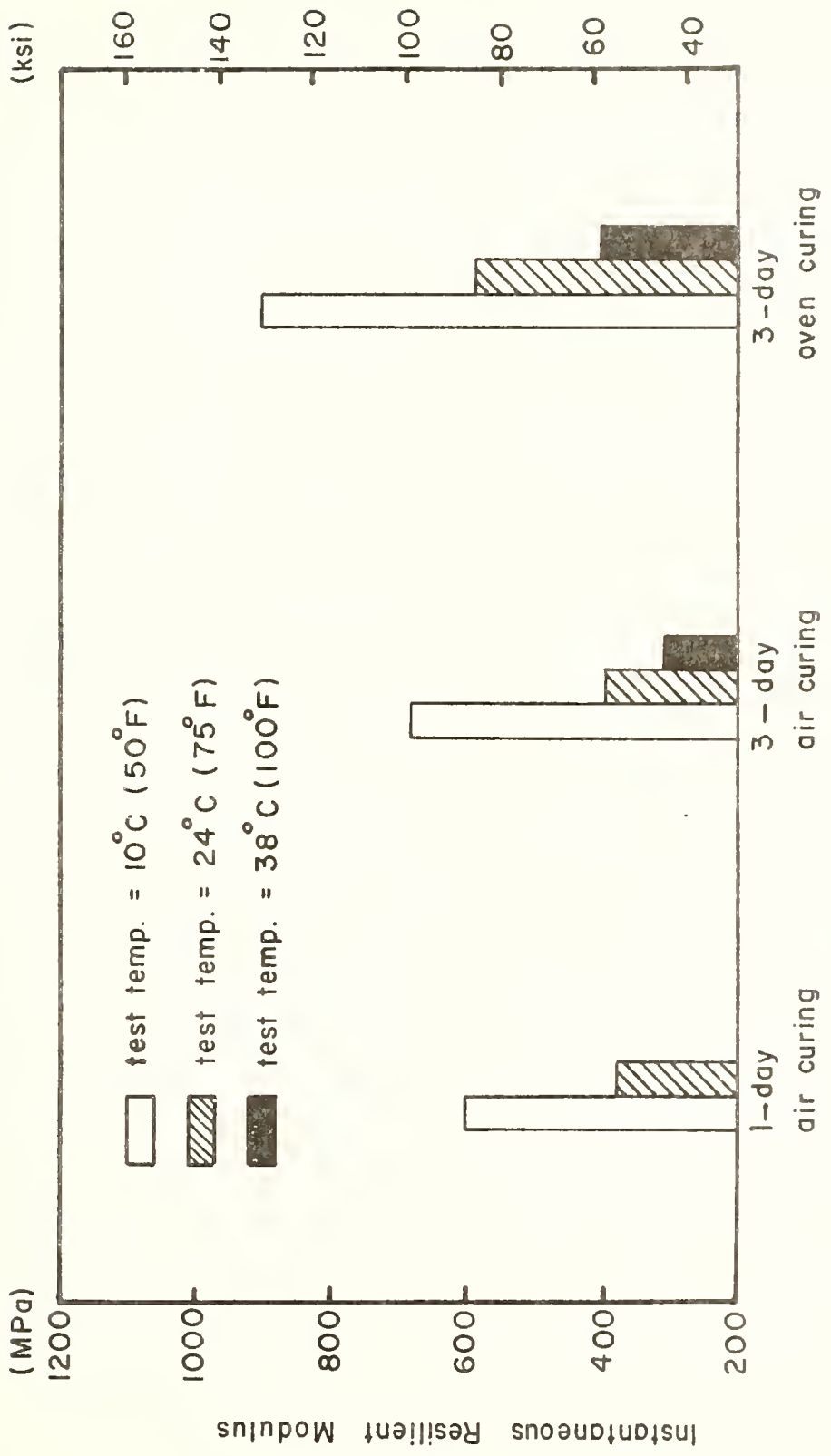
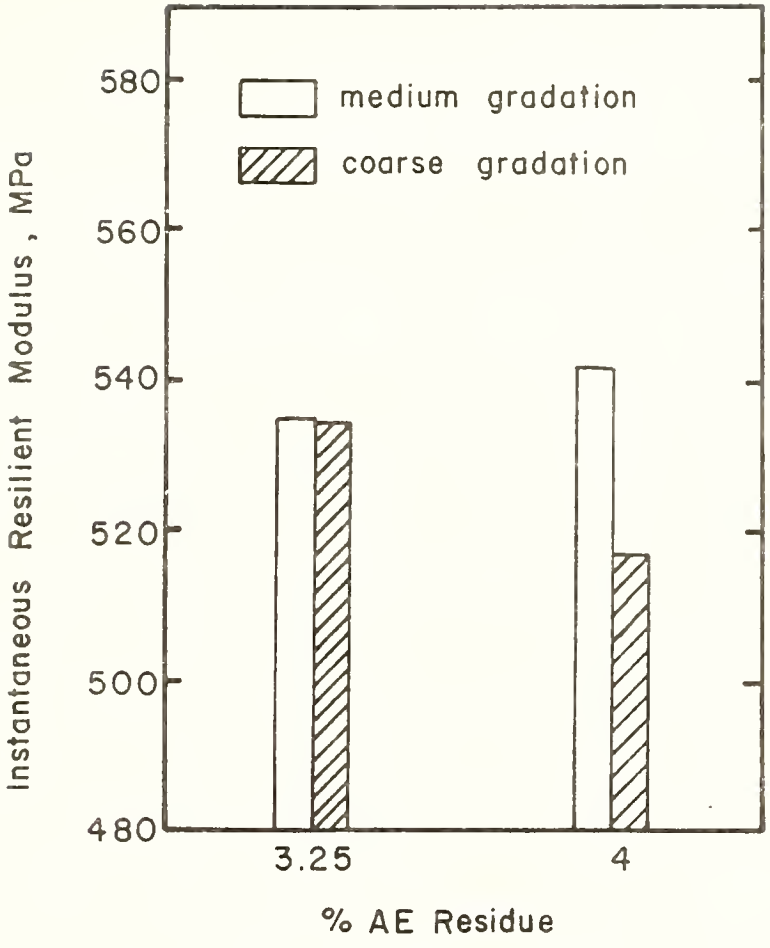


FIGURE 5.3, AVERAGE INSTANTANEOUS RESILIENT MODULUS VALUES AT DIFFERENT TEST TEMPERATURES AND CURING LEVELS

Thus, large M_R values were obtained for oven curing relative to the air curing. Also, 3-day air cured specimens gave larger M_R than 1-day air cured specimens.

Limestone mixtures gave larger M_R values than sand and gravel mixtures. The average M_R values of all limestone mixtures was 570 MPa (82.7 ksi), while sand and gravel mixtures gave an average M_R value of 494 MPa (71.6 ksi). Unlike sand and gravel, the rough surface and the angular shape of the limestone as well as its mineralogical composition increased the aggregate interparticle friction and improved the coating of asphalt residue on the aggregate particles, and consequently the M_R value increased.

Neither the asphalt emulsion content nor the aggregate gradation significantly affected the value of M_R at a level of significance of 0.5. However, the interaction effect of the asphalt emulsion content and aggregate gradation was significant. This conclusion draws the attention to the required amount of asphalt for the different aggregate gradations. Medium graded aggregate has more surface area than coarse graded aggregate. Therefore, medium graded aggregate needs a higher amount of asphalt emulsion than coarse graded aggregate to provide a good coating. This effect was observed on the M_R values of the mixtures as illustrated in Figure 5.4. It was found that increasing the asphalt residue content from 3.25% to 4% increased the average M_R value for medium graded mixtures and decreased it for coarse graded mixtures. The larger surface area of the medium graded aggregate required a larger amount of asphalt emulsion to improve the coating and to obtain a stiff mixture. On the other hand, increasing the amount of asphalt emulsion



Note: 1 MPa = 145 psi

FIGURE 5.4, EFFECT OF AGGREGATE GRADATION AND ASPHALT EMULSION CONTENT ON THE AVERAGE INSTANTANEOUS RESILIENT MODULUS

for coarse graded mixtures increased the thickness of the asphalt coating. Therefore, a less stable mixture was formed and small M_R values were obtained.

The interaction of asphalt emulsion content, aggregate type and curing had a significant effect on the M_R value for 10 and 24°C (50 and 75°F) test temperatures as may be seen in Figure 5.5. High average M_R values were obtained using limestone mixtures and 3-day oven curing compared to sand and gravel mixtures and 1-day air cuirng. In addition, mixtures with 4% asphalt residue content provided larger average M_R values than mixtures with 3.25% asphalt residue at 1-day air curing. However, at 3-day oven curing the opposite was true.

It was found also that the interaction of percent initial added moisture, curing and asphalt emulsion content had a significant effect on the M_R value for both 3-day air and oven curings (Figure 5.6). The interaction effect of 3-day oven curing with other mix components gave higher M_R values than 3-day air curing. Moreover, it was found that using 1.5% initial added moisture and 3.25% asphalt residue content at 3-day oven curing gave the largest average M_R value. Using 4.5% initial added moisture and 4% asphalt residue content at 3-day air curing gave the smallest average M_R value. Also, large average M_R values were obtained at 1.5% initial added moisture compared to 3 or 4.5% initial added moisture for the same asphalt emulsion content and curing level.

According to the ANOVA tests, it was found that the M_R value was largely affected by the interaction of asphalt emulsion content, test temperature and aggregate gradation for 3-day air and oven curings as may be seen in Figure 5.7. In most cases, medium graded mixtures gave

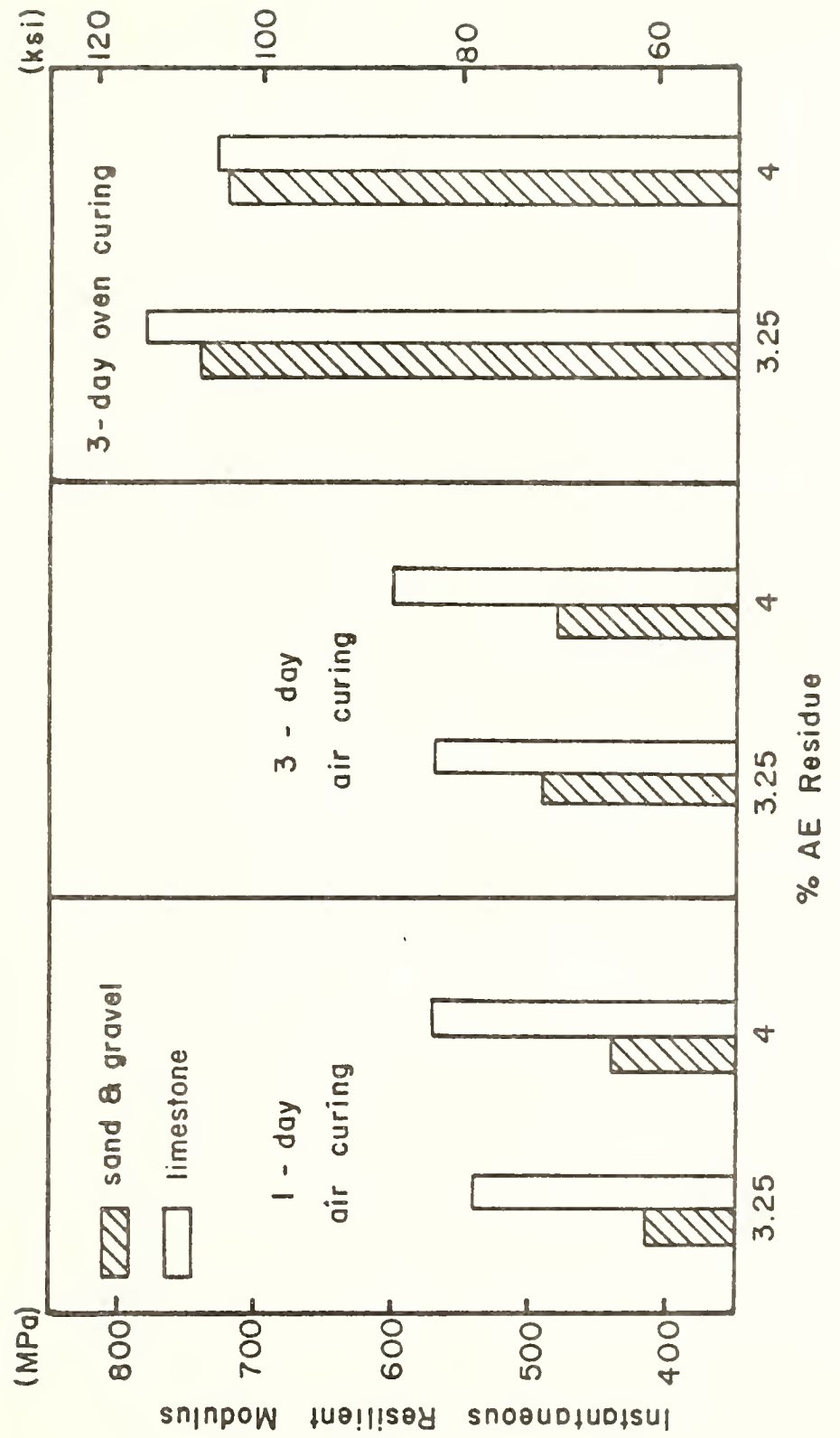


FIGURE 5.5, EFFECT OF AGGREGATE TYPE, ASPHALT EMULSION CONTENT AND CURING ON THE AVERAGE INSTANTANEOUS RESILIENT MODULUS AT 10 AND 24°C (50 and 75°F) TEST TEMPERATURES

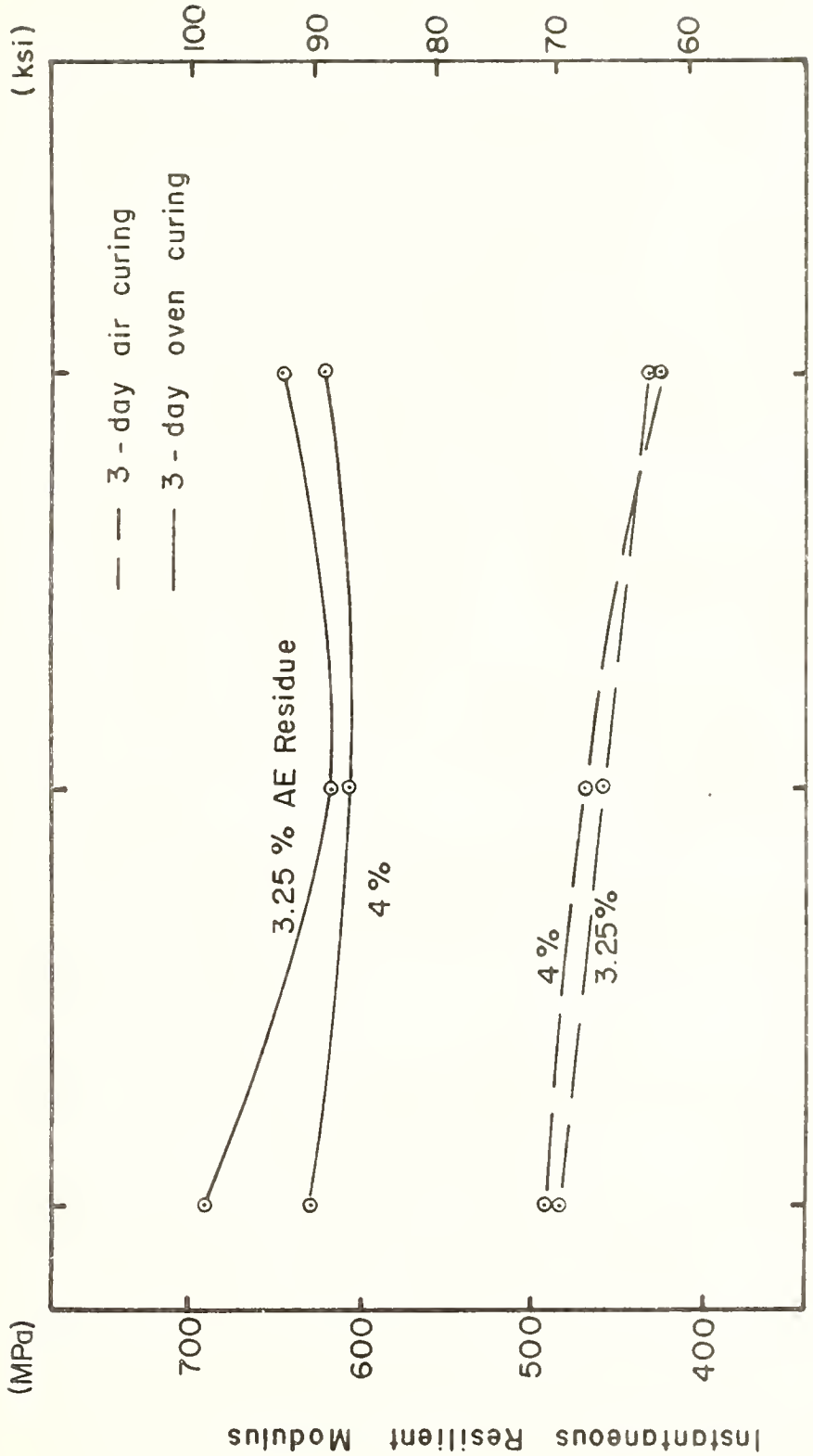


FIGURE 5.6 , EFFECT OF PERCENT ADDED MOISTURE, CURING AND ASPHALT EMULSION CONTENT ON THE AVERAGE INSTANTANEOUS RESILIENT MODULUS FOR 3-DAY AIR AND OVEN CURINGS

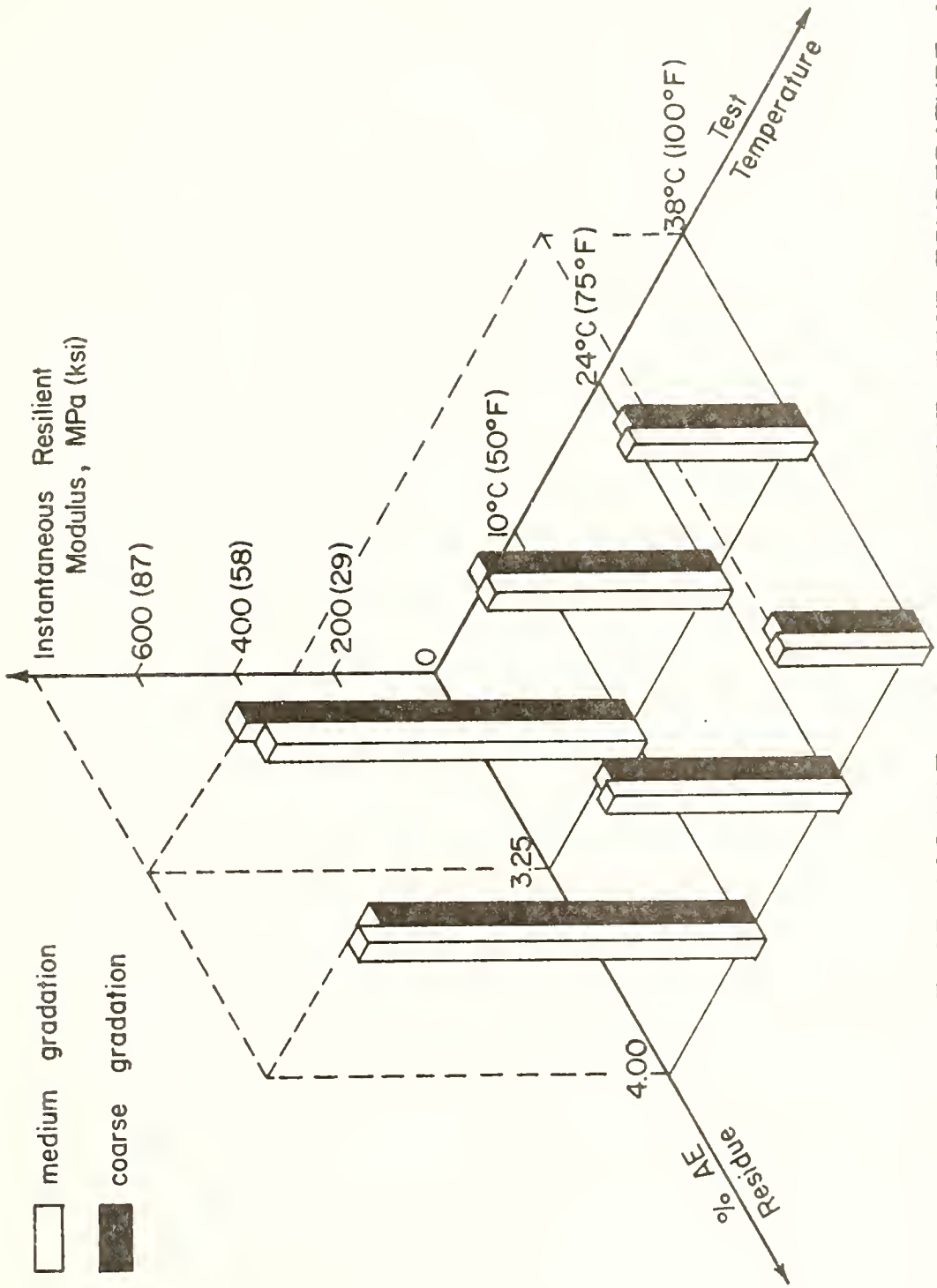


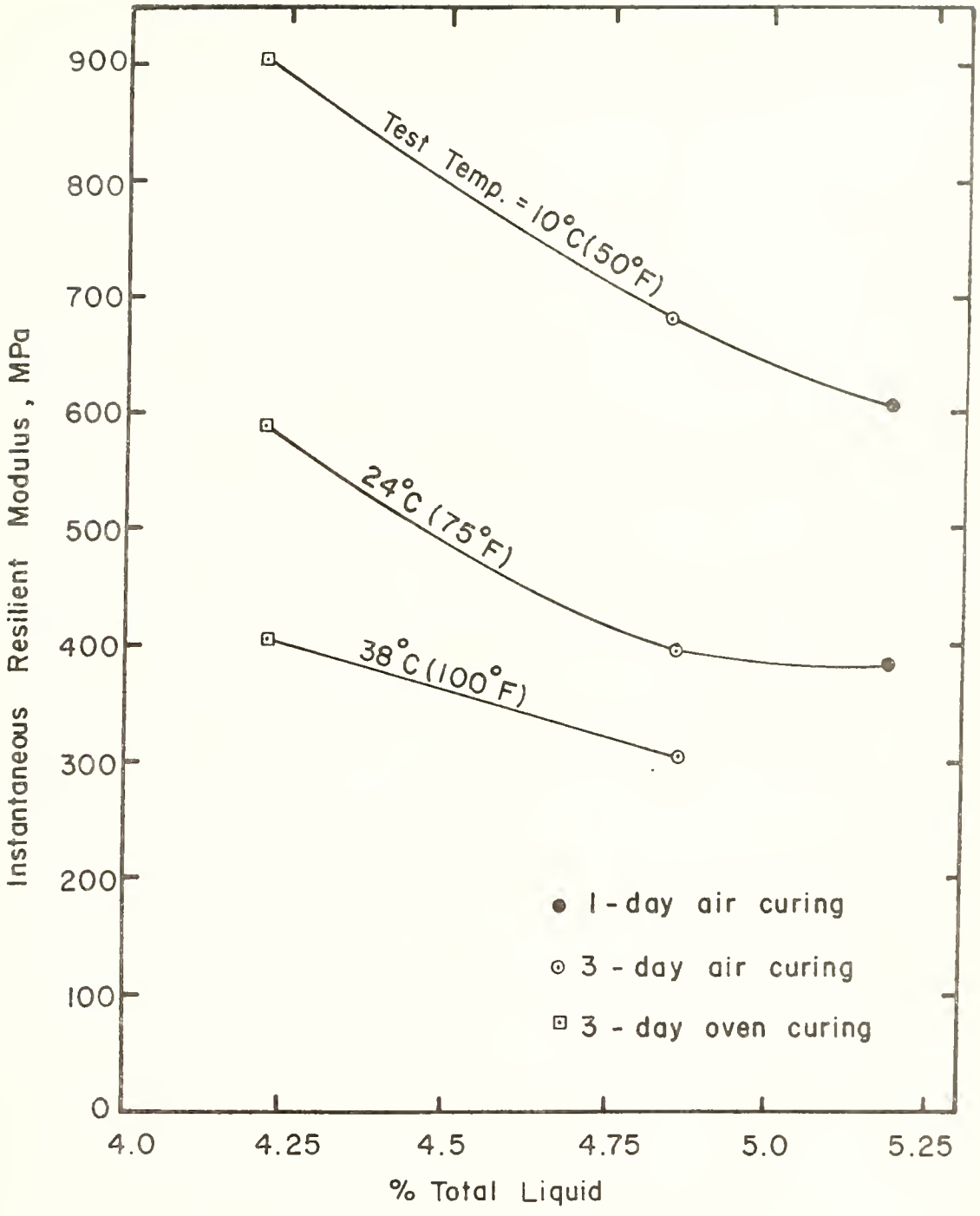
FIGURE 5.7, EFFECT OF ASPHALT EMULSION CONTENT, TEST TEMPERATURE AND AGGREGATE GRADATION ON THE INSTANTANEOUS RESILIENT MODULUS (3-day air and oven curings)

larger M_R values than coarse graded mixtures for the corresponding factor combinations. Large M_R values were obtained at low temperatures rather than high temperatures for the corresponding factor combinations.

The relationship between the instantaneous resilient modulus and the total liquid at time of testing for the different curing levels and test temperatures is shown in Figure 5.8. Increasing the curing level from 1-day air curing to 3-day air curing or 3-day oven curing for the same test temperature decreased the amount of total liquid and at the same time increased the M_R value. This indicates that the asphalt emulsion mixture builds up its strength by curing when water is evaporated leaving the asphalt residue adhering to aggregate particles. The largest effect of curing was indicated at 3-day oven curing at which the total liquid content decreased markedly and the resilient modulus value largely increased. It is obvious that the maximum value of M_R is obtained when all the moisture evaporates during the long-term curing process. It is shown also that the asphalt emulsion mixture is largely affected by test temperature for the different total liquid contents and curing levels.

5.4.2 Instantaneous Resilient Poisson's Ratio

Poisson's ratio in the classical sense is defined as the ratio of the lateral strain to the axial strain, caused by an axial load. Similar values of Poisson's ratio may be obtained using the diametral load in either the static or dynamic conditions, provided that the material is homogeneous, isotropic and linear elastic. Using the diametral repeated load test, Poisson's ratio may be obtained from Equation 5.2. In this study, the majority of the instantaneous resilient Poisson's ratios



Note: 1 MPa = 145 psi

FIGURE 5.8, AVERAGE INSTANTANEOUS RESILIENT MODULUS vs. AVERAGE TOTAL LIQUID AT TIME OF TESTING

ranged between 0.1 and 0.45 with an average of 0.314 for all specimens. A very small number of Poisson's ratio values were negative at the 10°C (50°F) test temperature. The reason for this could be due to the testing error provided that the actual deformation values of the specimens were very small at low temperatures. However, some Poisson's ratio values were larger than 0.5 at 38°C (100°F) test temperature. At high test temperatures, specimens were not firm enough so that tension cracks were developed after a few applications of load. These tension cracks caused an increase in specimen volume which increased the values of Poisson's ratio.

Poisson's ratio was largely affected by all main factors included in the study except aggregate gradation. The most important factors which affected the value of Poisson's ratio were test temperature and curing. The average Poisson's ratio values obtained at different curing levels and test temperatures are presented in Table 5.2. It is obvious that increasing the test temperature decreased the viscosity of asphalt residue and caused tension crack to develop which resulted in a large instantaneous horizontal deformation of the specimen and had a direct effect on increasing Poisson's ratio values (see Equation 5.2). Meanwhile, Poisson's ratio was decreased by increasing the curing level from one-day air curing to three-day air curing or three-day oven curing. Obviously, curing allowed water to evaporate and increased the consistency of the asphalt residue which resulted in harder mixes.

Increasing the asphalt emulsion residue content from 3.25 to 4% increased the lubrication between aggregate particles and consequently the average Poisson's ratio values for all specimens was increased from

Table 5.2 Average Instantaneous Resilient Poisson's Ratio Values for Different Curings and Test Temperatures

Curing	Test Temperature	Instantaneous Resilient Poisson's Ratio
1-day air curing	10°C (50°F)	0.160
	24°C (75°F)	0.393
3-day air curing	10°C (50°F)	0.130
	24°C (75°F)	0.344
	38°C (100°F)	0.596*
3-day oven curing	10°C (50°F)	0.049
	24°C (75°F)	0.307
	38°C (100°F)	0.534*

*The asphalt emulsion mixture did not meet the initial assumptions in the original derivation of equations.

0.291 to 0.338. In addition, changing the percent initial added moisture affected the value of Poisson's ratio. The average values of Poisson's ratio were 0.279, 0.341, and 0.322 using initial added moistures of 1.5, 3, and 4.5% of the dry weight of aggregate respectively.

The mixture performance was different when different types of aggregates were used. Sand and gravel mixtures gave higher Poisson's ratio values than limestone mixtures. This is because of the angular shape and the rough surface of limestone particles as opposed to the sand and gravel particles. An average value of 0.341 was obtained for Poisson's ratio using the different sand and gravel mixtures versus 0.228 using limestone mixtures.

The interaction effect of asphalt emulsion contents, aggregate type and initial added moisture on the average values of Poisson's ratio is illustrated in Figure 5.9. Mixtures containing 4% asphalt residue had larger Poisson's ratio values than mixtures containing 3.25% asphalt residue for the same aggregate type and initial added moisture. Also, in most combinations, high values of Poisson's ratio were obtained for mixtures containing 3% initial added moisture rather than 1.5 or 4.5%. In addition, limestone mixtures gave average values of Poisson's ratio smaller than sand and gravel mixtures for all combinations.

5.4.3 Unit Weight at Time of Compaction

The unit weight of the asphalt emulsion mixture at time of compaction is a measure of compatability of the mixture. It represents the unit weight of the pavement mixture during the field construction. The greater the unit weight during construction, the better the pavement will perform. High unit weights during construction prevent further

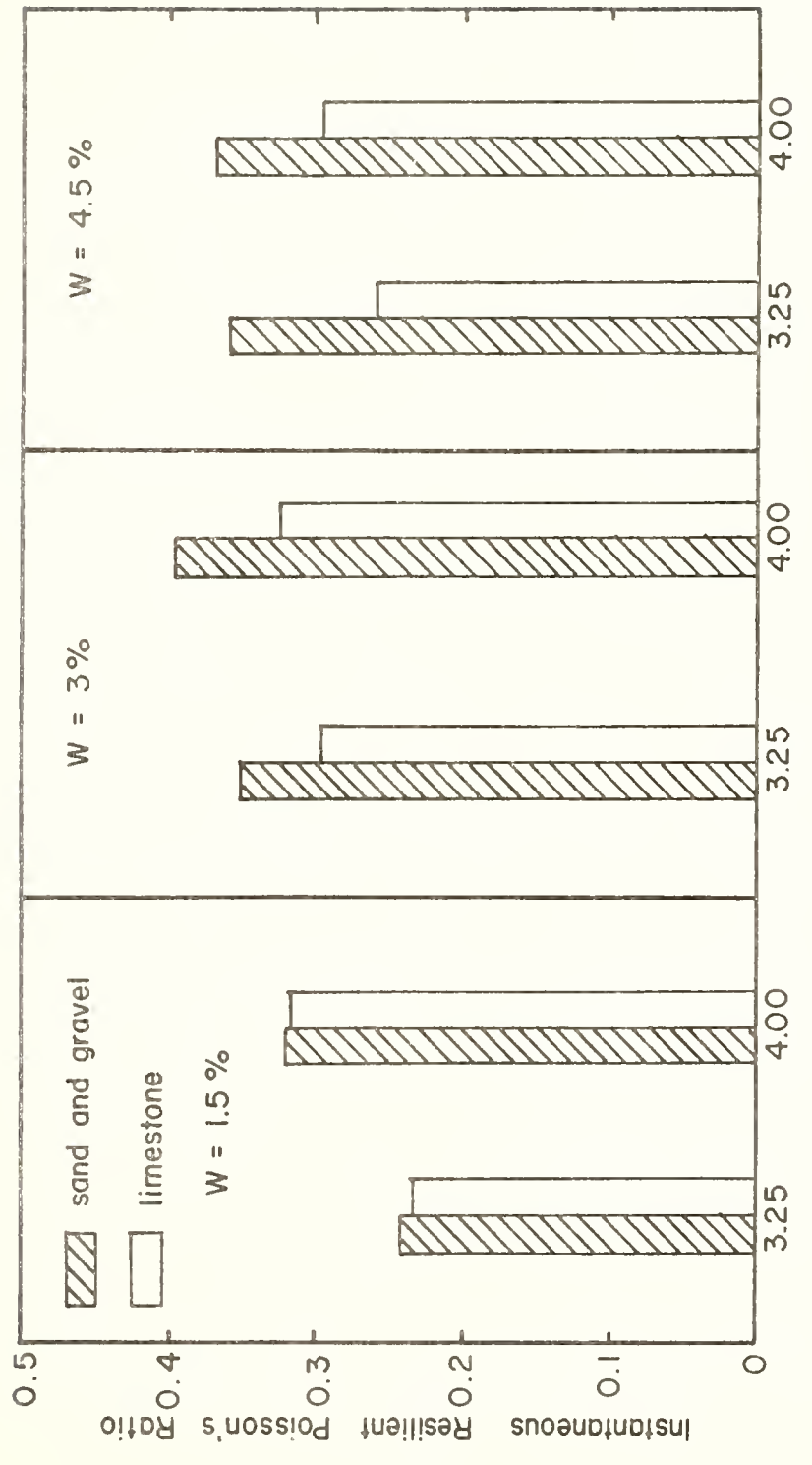


FIGURE 5.9, AVERAGE INSTANTANEOUS RESILIENT POISSON'S RATIO AS A FUNCTION OF ASPHALT EMULSION CONTENT, AGGREGATE TYPE AND INITIAL ADDED MOISTURE

compaction by traffic which has the effect of reducing rutting or excessive permanent deformation of the pavement. On the other hand, a certain amount of air voids in the mixture is needed to increase the curing rate and to improve the drainage in the pavement.

In this study, the wet unit weight of the mixture at time of compaction varied from 2280 to 2483 kg/m^3 (142.3 and 154.9 pcf respectively. It was largely affected by the asphalt emulsion content in the mixture. Increasing the asphalt emulsion content increases the lubrication between aggregate particles and allows more compaction to occur to the mixture, which in turn increases the unit weight. At the same time, increasing the asphalt emulsion content to a point allows more voids to be filled with asphalt which increases the unit weight as well. The average unit weight of the mixture at time of compaction increased from 2346 to 2386 kg/m^3 (146.4 and 148.9 pcf) when the asphalt residue increased from 3.25 to 4 as percents of the dry weight of aggregate respectively.

The value of the unit weight at time of compaction was significantly influenced by the interaction effect of asphalt emulsion content, aggregate type and aggregate gradation. The effect of these variables on the unit weight at time of compaction is depicted in Figure 5.10. Coarse graded mixtures gave an average unit weight lower than medium graded mixtures for the same aggregated type and asphalt emulsion content. It infers that medium graded aggregate would give relatively dense asphalt emulsion mixes compared to coarse graded aggregate. The maximum average unit weight at the time of compaction was obtained using the medium graded sand and gravel mixtures with 4% asphalt emulsion residue content.

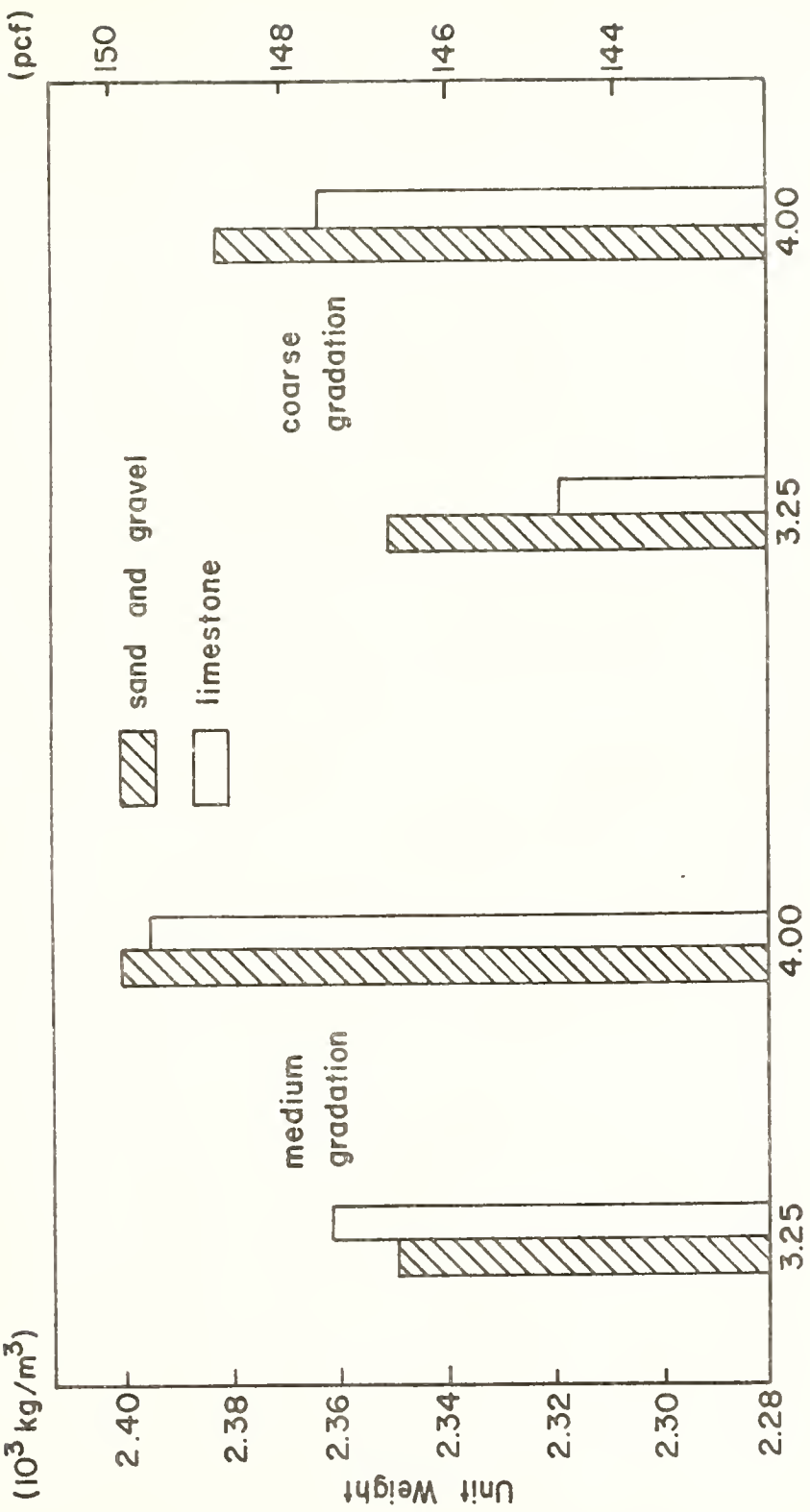


FIGURE 5.10, EFFECT OF ASPHALT EMULSION CONTENT, AGGREGATE TYPE AND AGGREGATE GRADATION ON THE AVERAGE UNIT WEIGHT AFTER COMPACTION

5.4.4 Unit Weight at Time of Testing

The wet unit weight of the specimens at time of testing (after curing), including the moisture portion, ranged from 2275 to 2457 kg/m^3 (142.0 and 153.3 pcf). It was significantly affected by the asphalt emulsion content, aggregate gradation and curing. Asphalt emulsion content affected the wet unit weight at the time of testing in the same manner as it did for the unit weight at time of compaction. The average value of the wet unit weight at time of testing increased from 2364 to 2388 kg/m^3 (147.5 and 149.0 pcf) when the asphalt residue content increased from 3.25 to 4% of the dry weight of aggregate respectively. Moreover, medium graded aggregate resulted in a more dense mixture and a higher wet unit weight than coarse graded aggregate. In addition, curing allowed water to leave the mixture which resulted in decreasing the wet unit weight.

The interaction of curing, aggregate gradation and aggregate type had a marked affect on the wet unit weight at test time (Figure 5.11). The average wet unit weight decreased gradually from one-day air curing to three-day air and oven curings for the same aggregate type and gradation. Also, medium graded limestone mixtures produced higher wet unit weights than medium graded sand and gravel mixtures for the same curing level. However, coarse graded sand and gravel mixtures gave higher wet unit weights than coarse graded limestone mixtures. In addition, for the same curing level, medium graded limestone mixtures produced higher wet unit weights than coarse graded limestone mixtures. Opposite trends were obtained for sand and gravel mixtures. As a result, in order to obtain a maximum wet unit weight for the mixture, the interaction affect

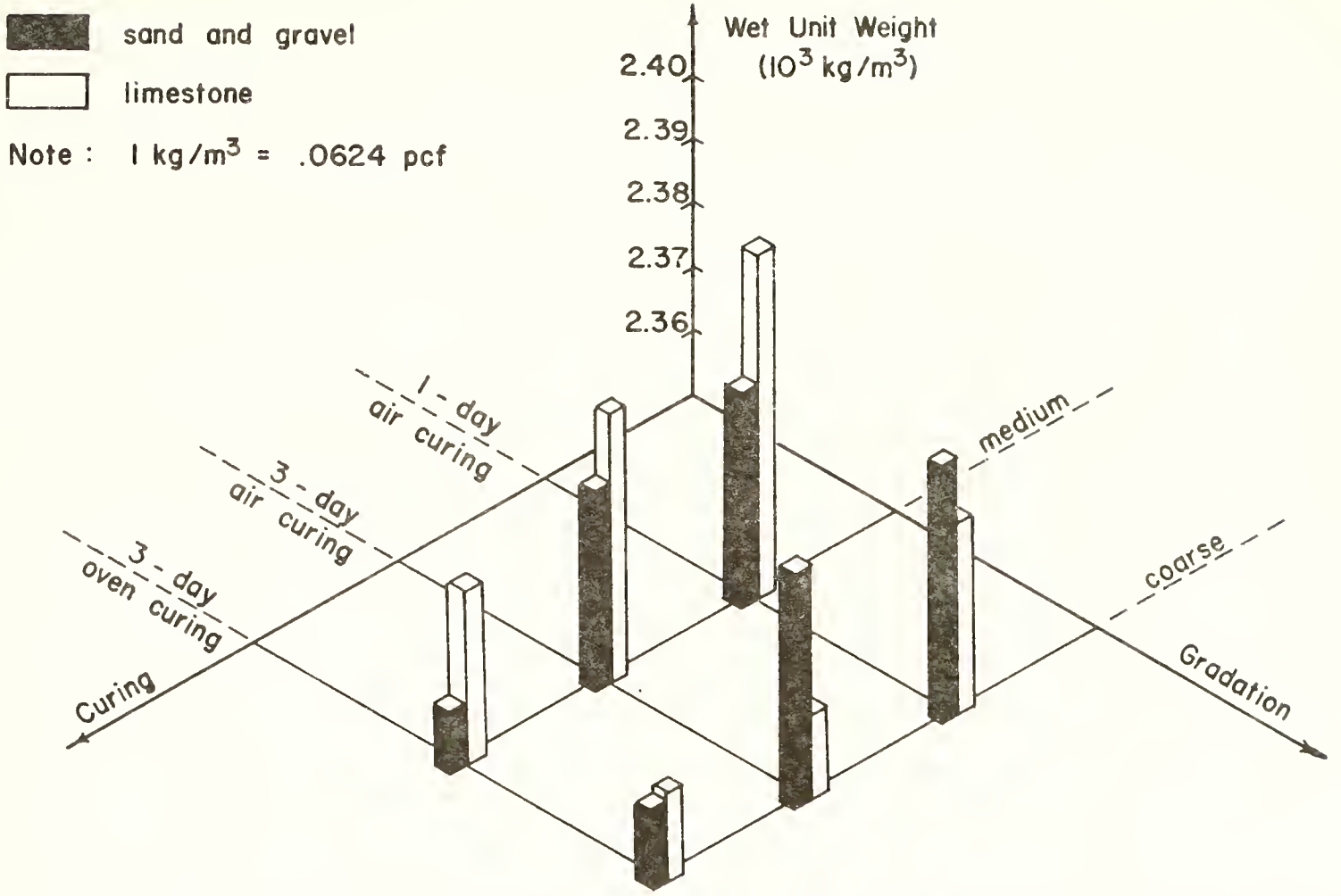


FIGURE 5.11, EFFECT OF CURING, AGGREGATE GRADATION AND AGGREGATE TYPE ON THE AVERAGE WET UNIT WEIGHT AT TIME OF TESTING

of aggregate type and gradation as well as the curing time should be taken into consideration.

The interaction effect of percent initial added moisture, aggregate type and aggregate gradation on the wet unit weight of the specimen was also significant. The maximum average wet unit weight was obtained for the medium graded limestone mixes with 4.5% initial added moisture, while the minimum average wet unit weight was obtained for the coarse graded limestone mixes with an initial added moisture of 1.5%.

The dry unit weight of the asphalt emulsion mixes, excluding the moisture portion, varied between 2252 kg/m^3 (140.5 pcf) and 2426 kg/m^3 (151.4 pcf). Similar to the wet unit weight, the dry unit weight was mainly affected by the asphalt emulsion content and aggregate gradation. When the asphalt residue content increased from 3.25 to 4% of the dry weight of aggregate, the dry unit weight increased from an average of 2342 to 2361 kg/m^3 (146.1 and 147.3 pcf respectively). Also, the medium graded mixtures contained lower air voids and consequently provided higher dry unit weights than the coarse graded mixtures.

The dry unit weight was significantly affected by the interaction of asphalt emulsion content, aggregate type and aggregate gradation as illustrated in Figure 5.12. Higher dry unit weights were obtained using medium graded limestone mixtures with 4% asphalt residue content. Coarse graded limestone mixtures with 3.25% asphalt residue produced lower dry unit weights. It was found also that curing did not have much of an effect on the dry unit weight of the mixture. Regardless of the amount of moisture that leaves the specimen during curing, the oven dried weight of the specimen remains the same and so does the dry unit

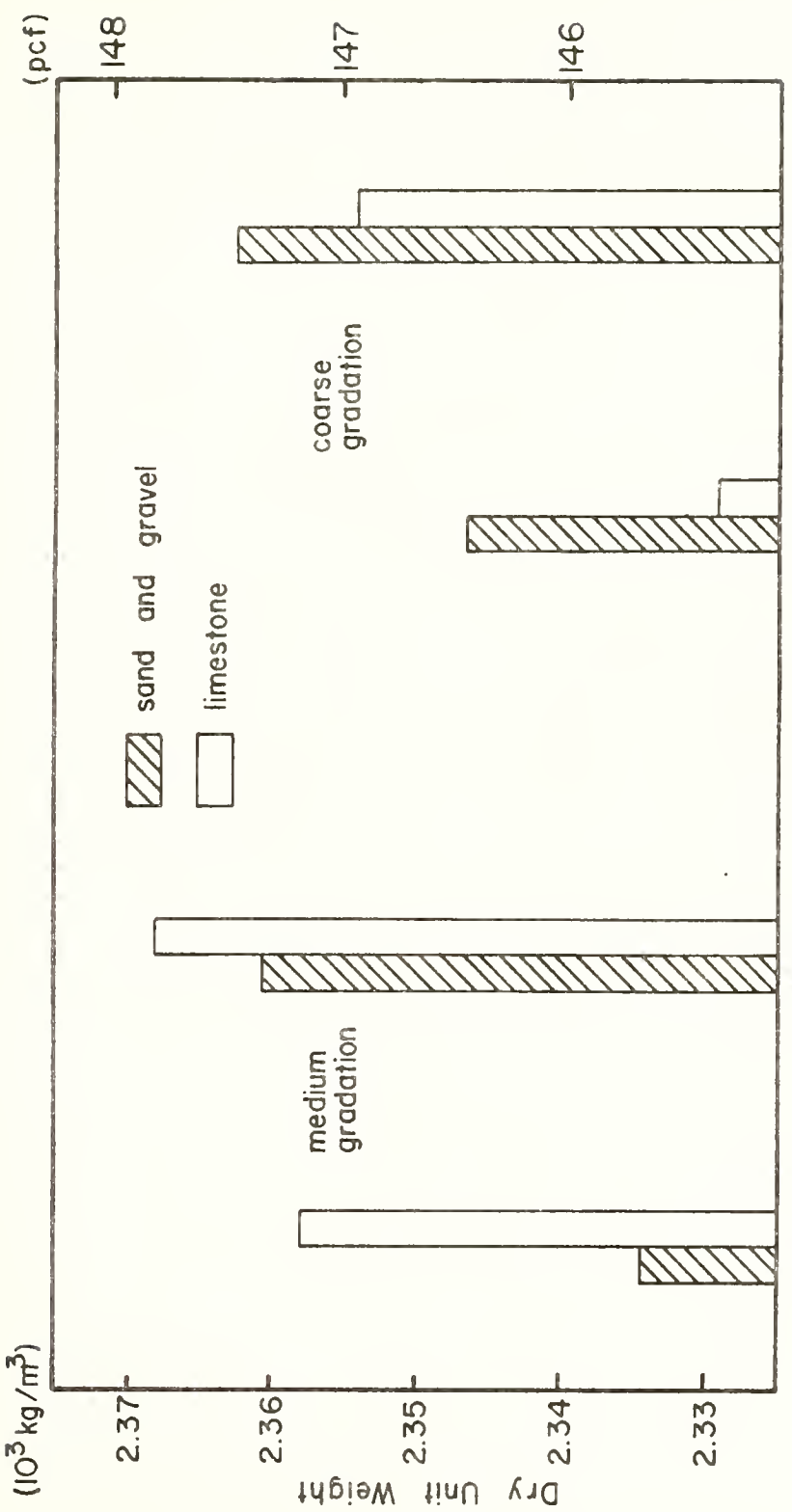


FIGURE 5.12, EFFECT OF ASPHALT EMULSION CONTENT, AGGREGATE TYPE AND AGGREGATE GRADATION ON AVERAGE DRY UNIT WEIGHT

weight. In addition, the dry unit weight of the mixture was directly correlated to the wet unit weight. The coefficient of correlation between the two parameters was 0.92 for all cases considered in the study.

5.4.5 Moisture Retained at Time of Testing

The moisture included in the asphalt emulsion mixture comes from the water added during the initial mixture preparation as well as the moisture included in the asphalt emulsion itself. The moisture portion is very important in the preparation of the cold-mixed asphalt emulsion mixture because it increases the workability of the mix and provides a uniform coating of asphalt residue on the aggregate particles. However, a large amount of moisture has an adverse effect on the mixture and reduces the strength. During the curing process, the water evaporates leaving the asphalt residue adhering to the aggregate. The rate of strength development of the asphalt emulsion mixture is directly related to the rate of moisture loss from the mixture. The study of the amount of moisture retained in the mixture at different curing stages and for different mix components is very important for the asphalt emulsion mixture characterization.

The percent moisture retained in the specimens at time of testing varied from 0.25 to 2.24% of the dry weight of aggregate with an average of 1.08% for all specimens in the study. It was highly affected by curing level. The average percent moisture retained at time of testing for the different curing levels is shown below

Curing	%Retained Moisture
1-day air curing, 22°C (72°F)	1.56
3-day air curing, 22°C (72°F)	1.23
3-day oven curing, 49°C (120°F)	0.60

The percent retained moisture was markedly reduced when oven curing was compared to 1-day and 3-day air curings. This means that oven curing, which represents the long-term curing process in the field, has a major effect on the reduction of the amount of moisture and consequently on the increase in the strength of the mixture. A few specimens were cured in the oven for more than 3 days at a temperature of 49°C (120°F) to check the amount of moisture loss. It was found that the amount of moisture lost due to the additional curing in the oven was not significant.

In addition to curing, the initial added moisture had an effect on the amount of moisture retained at the time of testing. The average moisture contents at test time were 0.99, 1.10 and 1.13% for initial added moistures of 1.5, 3.0 and 4.5% respectively. Moreover, the asphalt emulsion content affected the moisture retained at time of testing. Mixtures with high asphalt emulsion contents have low air void contents which result in the reduction of moisture lost from the specimen. Also, increasing the asphalt emulsion content increases the initial water content in the mixture because of the water included in the asphalt emulsion itself. Therefore, the average amount of retained moisture increased from 0.97 to 1.18% when the asphalt residue content increased from 3.25 to 4% by the dry weight of aggregate.

The moisture retained at the time of test was markedly affected by the interaction of curing and asphalt emulsion content as demonstrated in Figure 5.13. The rate of moisture lost from the mixture was larger in the case of oven curing when compared to air curing. Also, for the oven curing condition, the amount of moisture in the compacted mixture decreased largely at the beginning of the curing period, after which the moisture lost from the mixture was not significant. However, for the air curing condition, the reduction in the moisture content was gradual. Figure 5.13 shows also that decreasing the asphalt emulsion content increases the rate of moisture lost from the mixture. This effect was large in the case of oven curing when compared to air curing. In other words, increasing the air voids in the mixture increases the effect of oven curing more than air curing.

The ANOVA tests showed also that the interaction of initial added moisture content and curing had a significant effect on the percent retained moisture at testing time. The affect of these factors is illustrated in Figure 5.14. Statistical analysis indicated that the initial added moisture had a significant effect on the retained moisture at one-day air curing. However, for a larger curing time and/or higher temperature, the moisture retained in the mix was not affected by changing the initial added moisture.

5.4.6 Total Liquid at Time of Testing

The total liquid at the time of testing is one of the characteristics used frequently in the evaluation of asphalt emulsion mixes. The liquid content in the mixture is the sum of the asphalt emulsion residue content and the amount of retained moisture. The overall values of the

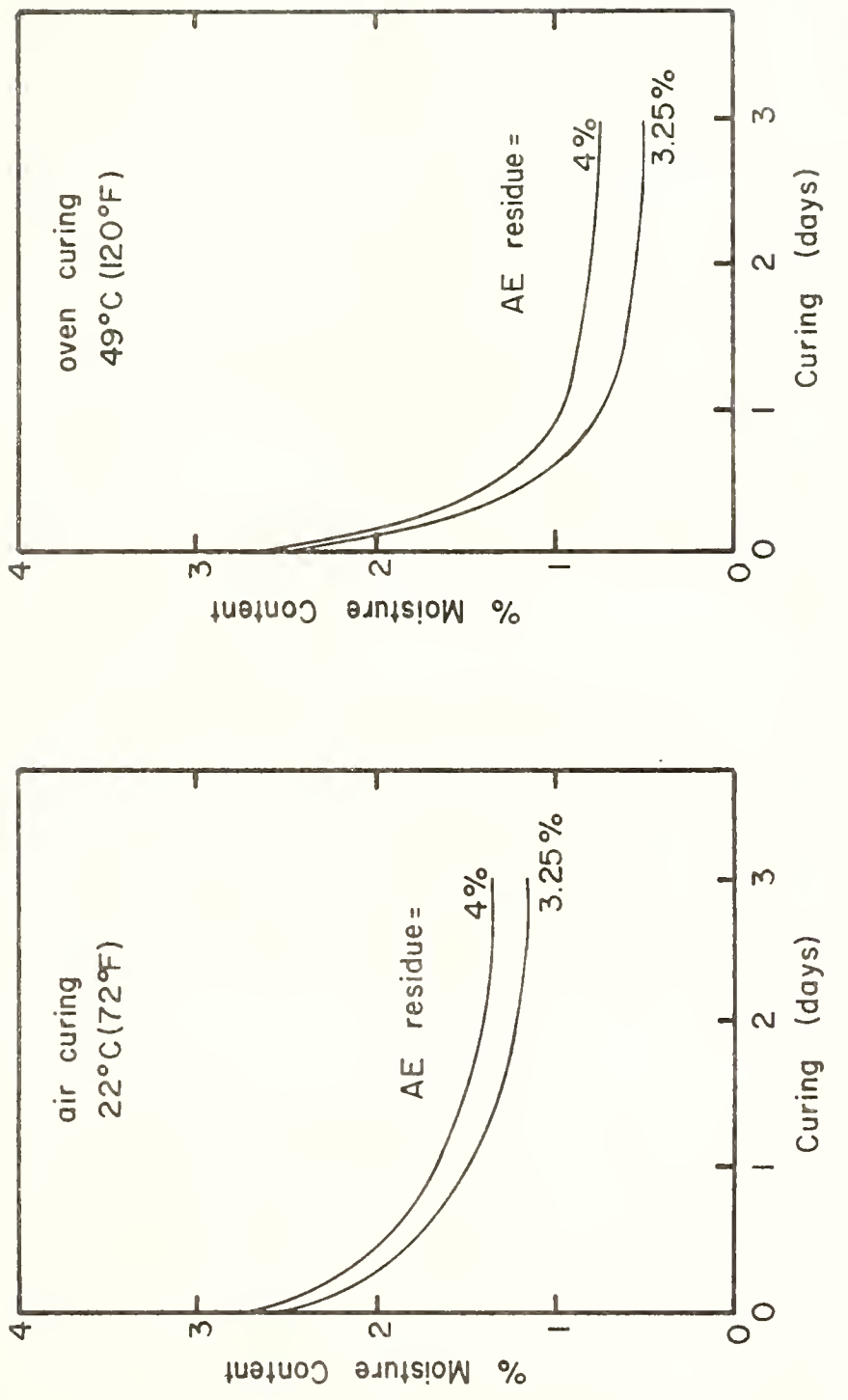


FIGURE 5.13, EFFECT OF AIR AND OVEN CURINGS ON MOISTURE CONTENT AS A PERCENT BY WEIGHT OF DRY AGGREGATE

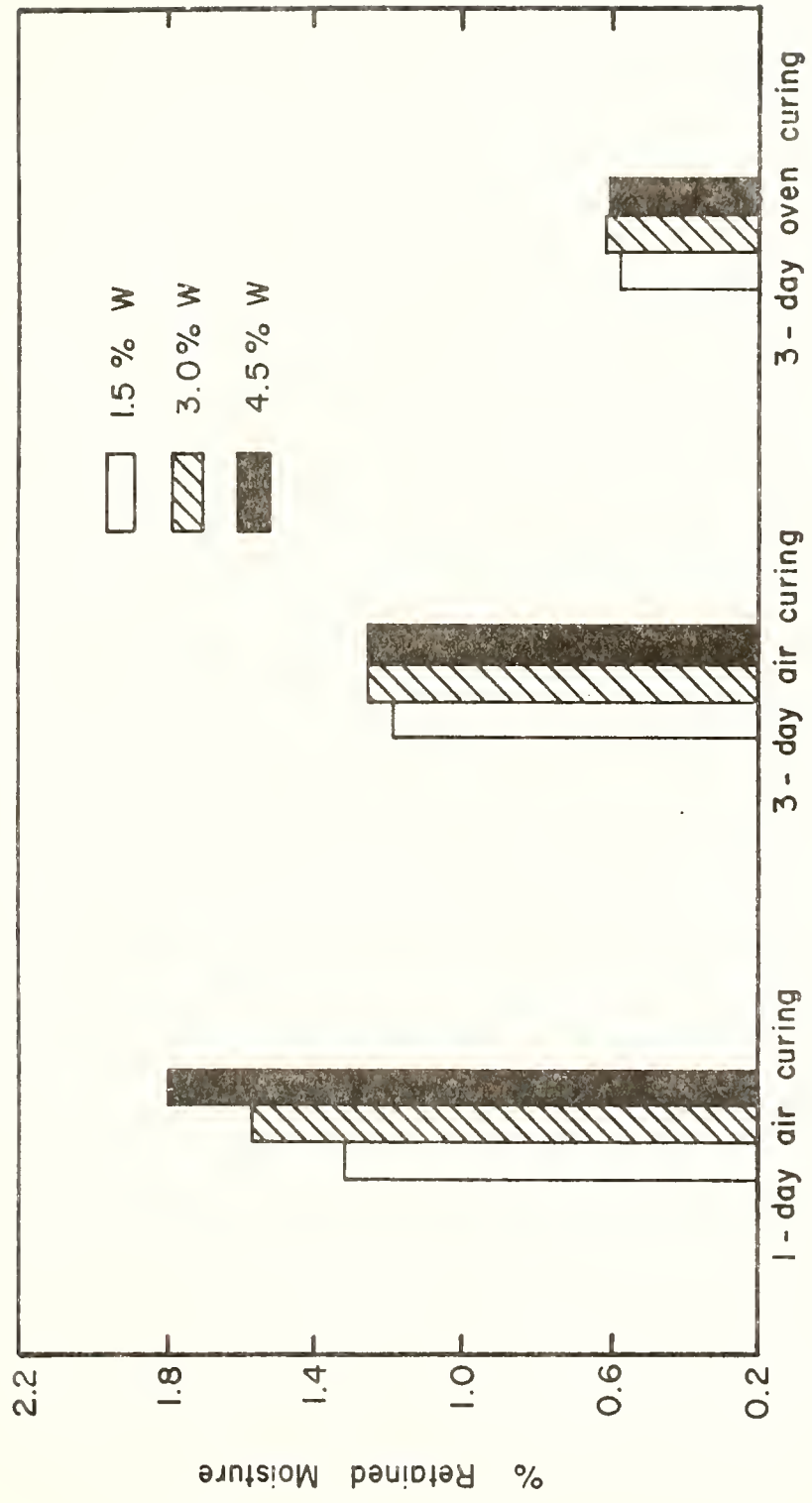


FIGURE 5.14, INFLUENCE OF INITIAL ADDED MOISTURE AND CURING ON THE AVERAGE MOISTURE RETAINED AT TIME OF TESTING

total liquid at time of testing for all specimens ranged between 3.50 and 6.19 as percents of the aggregate dry weight. The average total liquid at testing time was 4.70% for all mixtures included in the study.

The total liquid in the mixture at time of testing was mainly affected by the same factors which affected the amount of retained moisture. It was largely affected by asphalt emulsion content, percent initial added moisture and curing time. It increased from an average of 4.22% to 5.18% when the asphalt residue content increased from 3.25 to 4% respectively. It was found also that increasing the initial water content in the mixture increased the amount of total liquid after curing. When the initial added moisture values were 1.5, 3, and 4.5% of the dry weight of aggregate, the average total liquid values were 4.62, 4.73, and 4.76% respectively. In addition, increasing curing time and/or temperature allowed more moisture to evaporate and consequently decreased the amount of total liquid in the mixture. Average values of total liquid were 5.19, 4.86, and 4.22% for curing levels of 1-day air curing, 3-day air curing and 3-day oven curing respectively.

The interaction effect of asphalt emulsion content, initial added moisture and curing on the percent total liquid in the mixture at time of testing is shown in Figure 5.15. In general, the total liquid in the mixture decreased by increasing the curing, decreasing the initial added moisture and decreasing the asphalt emulsion content. The effects of the asphalt emulsion content in the mixture, represented by the slopes of the lines in the graphs, were almost the same for the different curing levels and initial added moistures. However, the effect of initial moisture content added to the mixture on the amount of total liquid was

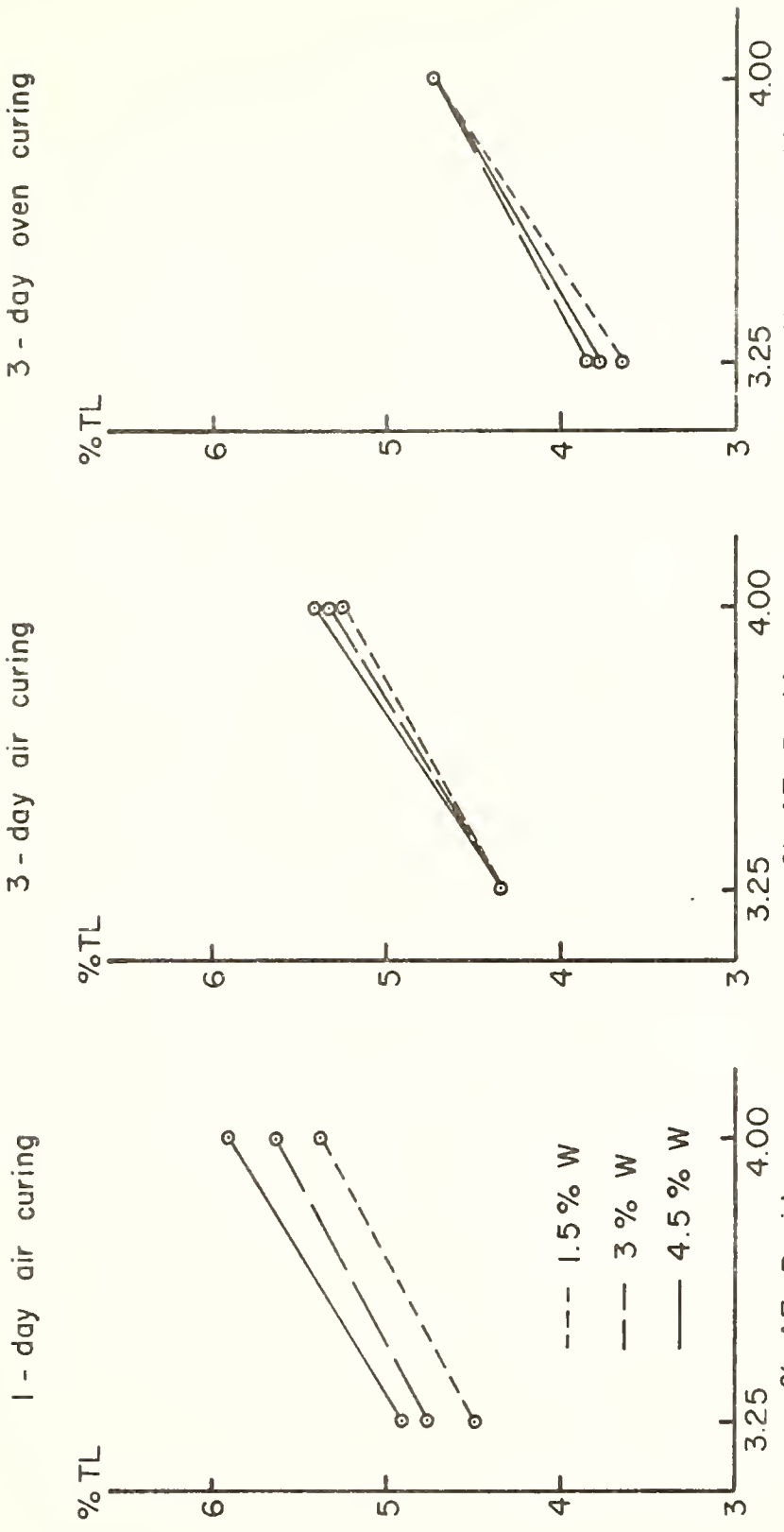


FIGURE 5.15, AVERAGE PERCENT TOTAL LIQUID AS A FUNCTION OF CURING, ASPHALT EMULSION CONTENT AND INITIAL ADDED MOISTURE

apparent at 1-day air curing compared to 3-day air and oven curings.

5.4.7 Voids at Time of Testing

a. Air Voids

The amount of air voids in the asphalt emulsion bases is an influential factor which affects the curing rate of the mixture and improves the drainage in the pavement. On the other hand, increasing the air voids increases the excessive permanent deformation that could be caused by traffic (or rutting). In addition, high amount of air voids increases the moistures absorption in the asphalt emulsion mixes which increases the potential of stripping or weakening the bond between asphalt and aggregate. An optimum amount of voids is needed to obtain an efficient performance of the mixture in the field.

In this study the air voids were calculated on the bases of the apparent specific gravity of the aggregate and assuming no asphalt was absorbed into the aggregate. The average air voids for all specimens in the study was 6.14% of the total volume, with a maximum value of 11.12% and a minimum of 2.18%. This wide range of percent air voids at time of testing occurred because of the large effect of asphalt emulsion content, curing, aggregate type and aggregate gradation.

Increasing the asphalt emulsion content reduced the air voids in the mix. The average air void was 7.30% when the asphalt emulsion residue was 3.25%, while it dropped to 4.98% when the asphalt emulsion residue was 4% of the dry weight of aggregate. In addition to the asphalt emulsion content, curing allowed moisture to evaporate which resulted in increasing the air voids. The average values of air voids in the mixture were 4.97, 5.87, and 7.19% for one-day air curing, three-day air

curing and three-day oven curing respectively.

Limestone mixtures gave a larger amount of air voids than sand and gravel mixtures. The average air voids was 6.61% in case of limestone mixes while it was 5.67% in case of sand and gravel mixes. In addition to aggregate type, aggregate gradation affected the amount of air voids in the mixture. Medium aggregate gradation gave a smaller percent air voids in the mixture than the coarse aggregate gradation. On the average, medium graded aggregate mixtures gave an air voids percent of 5.95, while coarse graded mixtures gave a percent of 6.33.

The interaction of asphalt emulsion content, curing, initial added moisture and aggregate type had a large effect on percent of air voids in the mixture. Figure 5.16 shows the different percent air voids values for various combinations of these factors. For all the corresponding factor combinations, 3.25% asphalt emulsion residue content produced higher air voids than 4% residue. Also, 3-day oven curing gave large amounts of air voids than 3-day air curing, while 1-day air cured mixtures gave the smallest air voids for the same levels of other factors. Moreover, limestone mixtures gave higher air voids percents than sand and gravel mixtures for almost all combinations of factors.

The percent air voids in the asphalt emulsion mixture was closely related to the percent total liquid at time of testing. For sand and gravel mixtures, the correlation coefficient between the two parameters was -0.91, while it was -0.80 for limestone mixtures. The relationship between the air voids and total liquid for both sand and gravel mixtures and limestone mixtures are shown in Figures 5.17 and 5.18 respectively. Linear relationships exist between the two variables as shown in the two

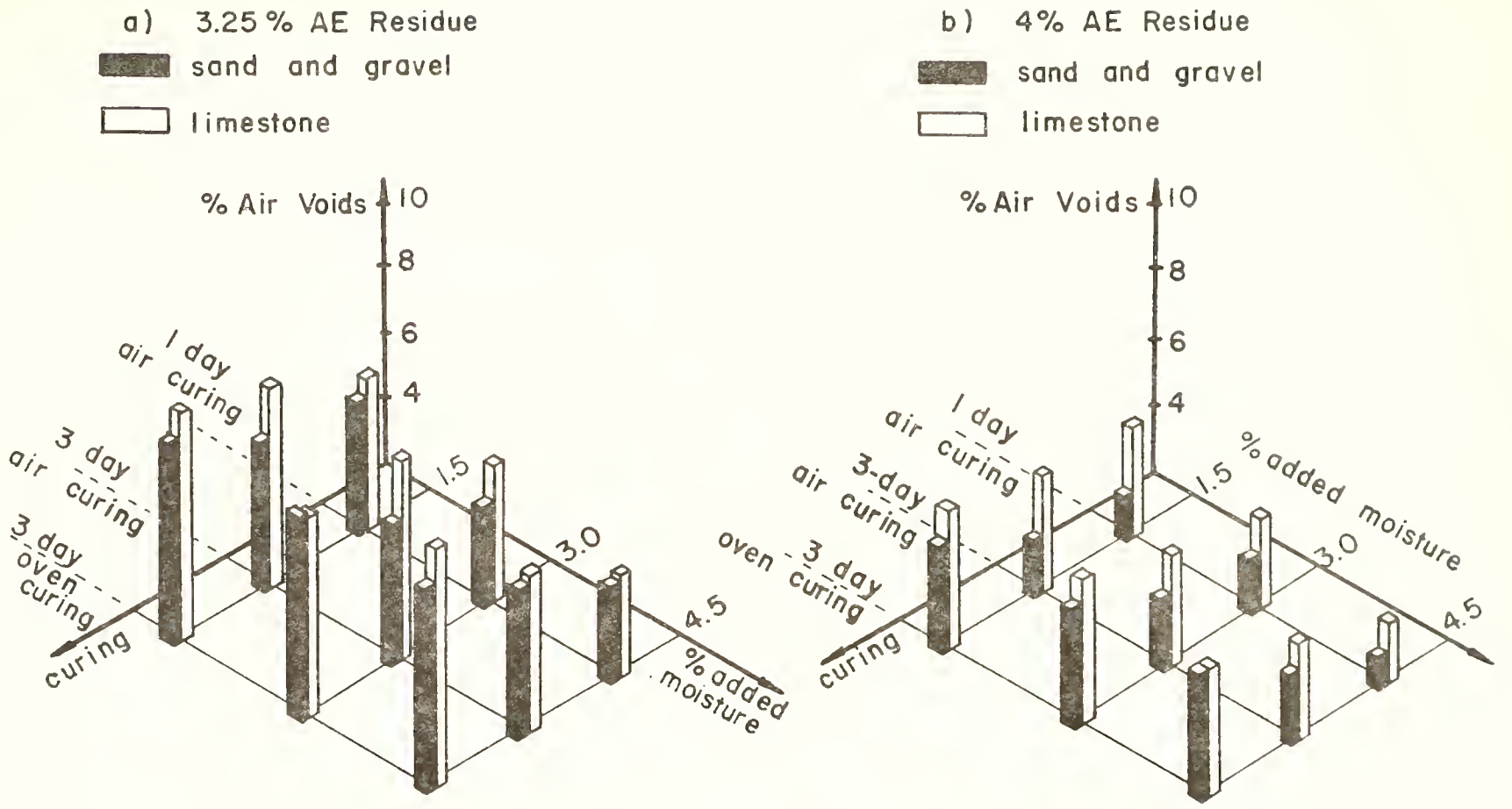


FIGURE 5.16 , INFLUENCE OF ASPHALT EMULSION CONTENT, CURING, INITIAL ADDED MOISTURE AND AGGREGATE TYPE ON AIR VOIDS AT THE TIME OF TESTING

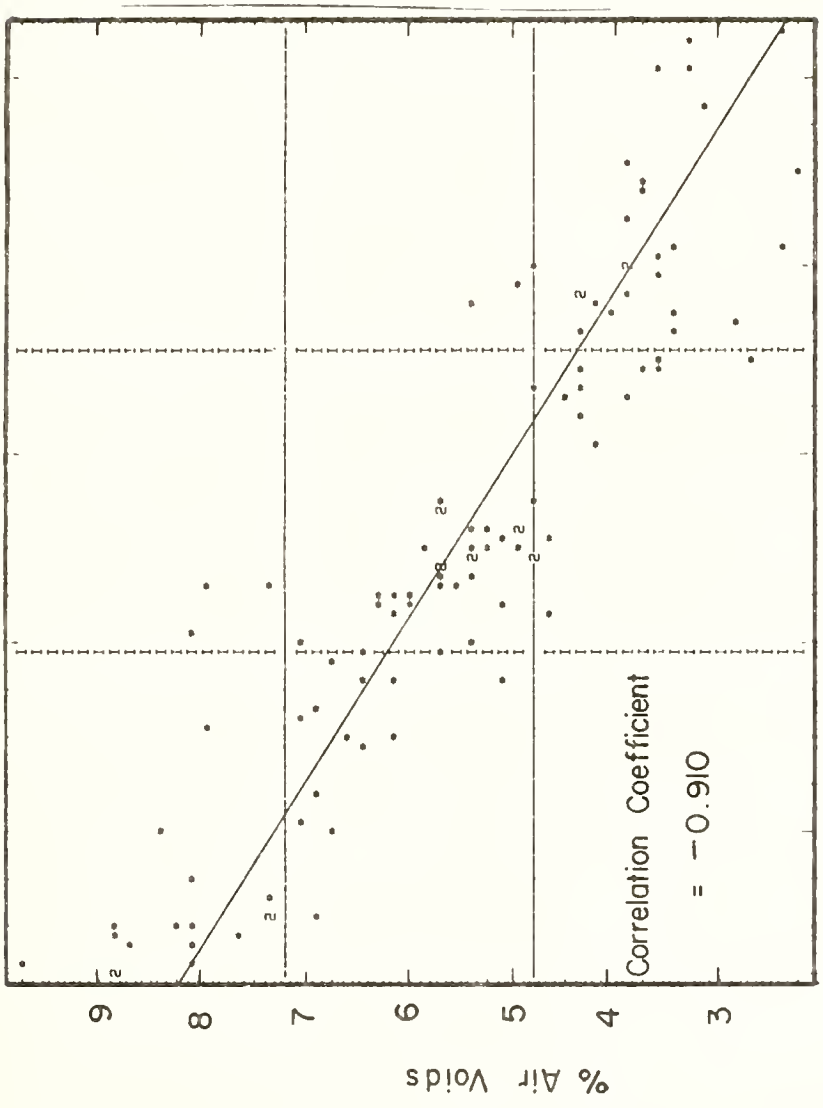


FIGURE 5.17, RELATIONSHIP BETWEEN AIR VOIDS AND TOTAL LIQUID AT TIME OF TESTING FOR SAND AND GRAVEL MIXTURES

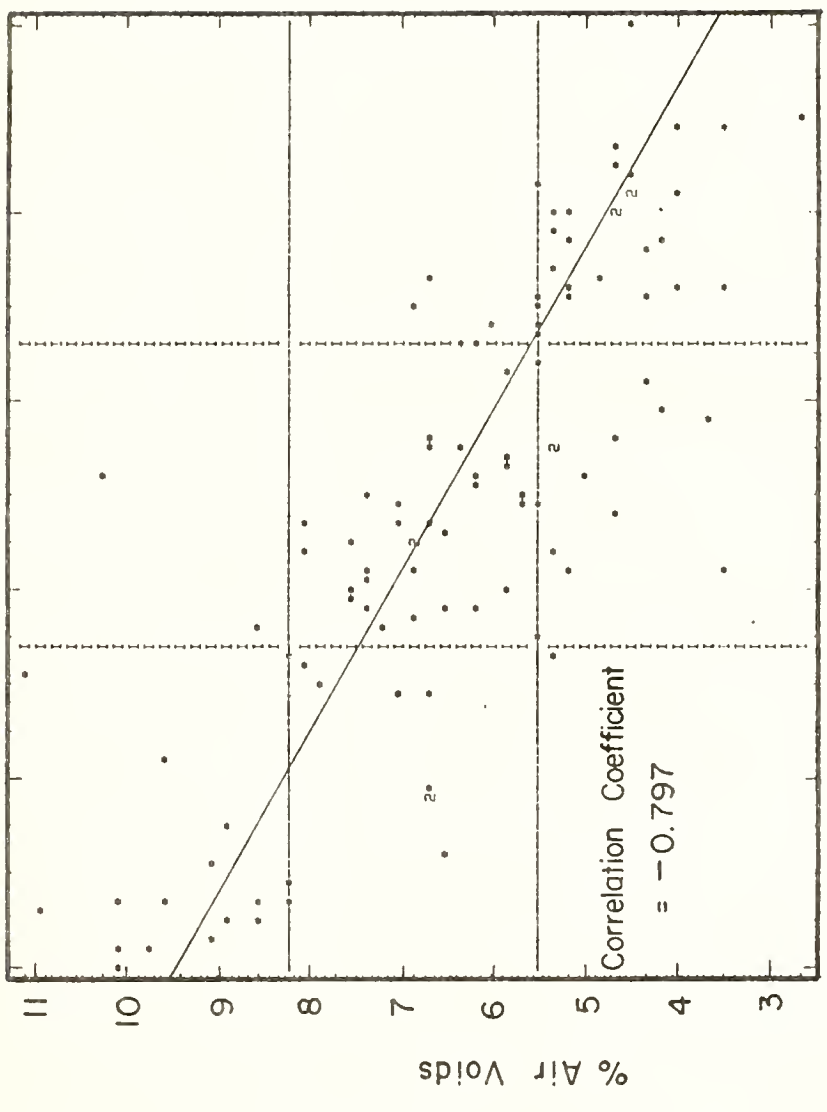


FIGURE 5.18, RELATIONSHIP BETWEEN AIR VOIDS AND TOTAL LIQUID AT TIME OF TESTING FOR LIMESTONE MIXTURES

figures. In addition to the total liquid, the percent air voids was directly correlated to the wet unit weight of the mixtures at time of testing. The correlation coefficient between the two variables was -0.85 for all mixtures tested in the study.

b. Total Voids

The total voids are the sum of air voids and voids filled with moisture in the compacted asphalt emulsion mixture. If the mixture is cured for a long period of time, almost all the amount of moisture evaporates and the percent air voids approaches the percent total voids. The total voids affect the density, the amount of water that may be absorbed into the mix, and the potential for permanent deformation or rutting of the mixtures.

The average total voids for the different mixtures in the study was 8.58% of the total volume. The maximum value of total voids for individual specimens was 13.81% and the minimum value was 5.57% of the total volume. The percent total voids was markedly affected by asphalt emulsion content, aggregate type and aggregate gradation. Increasing the asphalt emulsion content decreased the total voids percent. Also, sand and gravel mixtures gave a smaller total voids than limestone mixtures. In addition, for sand and gravel mixtures, the medium gradation gave larger percents of total voids than the coarse gradation, while for limestone mixtures the opposite was true. The percents of total voids at time of testing for the different asphalt emulsion contents, aggregate types and aggregate gradations are presented in Table 5.3.

The value of the total voids at testing time was not affected by curing because curing reduces the amount of water in the mixture but the

Table 5.3 Percents of Total Voids at Time of Testing for Different Asphalt Emulsion Contents, Aggregate Types and Aggregate Gradations

Aggregate Type	Aggregate Gradation	Asphalt Emulsion Content	
		3.25%	4%
Sand and Gravel	Medium	9.31	7.15
	Coarse	8.79	7.13
Limestone	Medium	9.33	7.92
	Coarse	10.58	8.44

amount of total voids remains the same. In addition, it was found that the total voids were highly correlated to the air voids. The correlation coefficient of two parameters was 0.82 for all the cases considered in the study.

c. Voids in the Mineral Aggregate (VMA)

The voids in the mineral aggregate, VMA, are the intergranular void spaces between the aggregate particles in the compacted asphalt emulsion mixes. They include air voids, asphalt residue and moisture retained in the mixture expressed as a percent of the total volume. The VMA is a measure of the mixture components which is frequently used for asphalt mixture characterization.

The VMA of the individual specimens in the study ranged from 14.27% to 20.42% of the total volume of the mixture. The average VMA for all specimens was 16.70%. It was mainly affected by the interaction of aggregate type and gradation. The average values of % VMA for the different combinations of aggregate types and aggregate gradations are shown in Table 5.4.

Table 5.4 Average % VMA for Different Aggregate Types and Gradations

Aggregate Type	Medium	Coarse
Sand and gravel	16.33	16.12
Limestone	16.81	17.55

The average % VMA was higher for limestone mixtures than for sand and gravel mixtures. Also, for sand and gravel mixtures, the medium gradation gave higher average % VMA value than the coarse gradation. Howev-

er, for limestone mixtures, the coarse gradation produced higher average values than the medium gradation.

5.5 Water Sensitivity Test

The effect of water on the performance of the asphalt emulsion treated bases was evaluated using a modification of the Asphalt Institute water sensitivity test (5). This test was found to be important for the evaluation of the sensitivity of the asphalt emulsion mixes to water (27). The test allows specimens to absorb a reasonable amount of water when compared to the normal field conditions and thus does not severely affect the specimen. The relatively low resistance of the mixture to water damage during the early curing stages due to the lack of bond between the mix components and the slow developments of strength (53) are thereby taken into consideration.

In this test, specimens were weighed after they have been cured for the required amount of time. Specimen were placed in a vacuum chamber (Figure 4.19) and were subjected to a vacuum of 30 mm Hg for one hour. At the end of this period, 22°C (72°F) water was slowly drawn by the vacuum into the bottom of the chamber until the specimens were submerged at least a half inch below the surface. The vacuum was then released and the specimens were transformed to a 22°C (72°F) water bath and left to soak for 24 hours. The saturated surface dry weight of the specimens were determined and the resilient modulus test was performed. One test temperature of 24°C (72°F) was used in this experiment. After the resilient modulus test was completed, specimens were broken apart and dried in a forced draft oven for 24 hours at 110°C (230°F) then reweighed. Measurements that were determined from the test were as follows:

1. Instantaneous resilient Poisson's ratio of the vacuum saturated specimens, which was determined in the same way as the dry specimens (see Equation 5.2).
2. Instantaneous resilient modulus of the vacuum saturated specimens using the same procedure as used for dry specimens (see Equation 5.3).
3. Moisture contents of the specimens before and after vacuum saturation expressed as percents by weight of the dry aggregate.
4. Moisture absorption of the vacuum saturated specimens (moisture pick-up) as a percent by weight of the dry aggregate; which is the difference between percent moisture contents after and before vacuum saturation.
5. Total liquid of the vacuum saturated specimens as a percent by weight of the dry aggregate; which is the sum of percent asphalt residue content and percent moisture content after vacuum saturation.

Factors that were considered in the study were as follows (see table 5.1):

1. Aggregate type, two types of aggregate were used; sand and gravel mixture and limestone.
2. Asphalt emulsion residue content; 3.25 and 4% of the dry weight of aggregate.
3. Curing; two levels of curing were considered which were 1-day air curing and 3-day oven curing at 49°C (120°F).

One aggregate gradation was used which was the medium gradation, MG (Figure 3.1). 3% initial moisture were added to all mixtures by weight

of the dry aggregate. Three replicates for the different factor combinations were tested. A comparative study was performed between vacuum saturated specimens and the corresponding specimens tested in the dry condition.

Studying the effect of the different factors considered in the investigation, it was found that asphalt emulsion content and curing had marked effects on the resilient characteristics of the vacuum saturated specimens. The average M_R values of dry and vacuum saturated specimens for the different asphalt emulsion contents and curing levels are shown in Figure 5.19. In most cases, dry specimens gave average M_R values larger than vacuum saturated specimens. Mixtures contained 3.25% asphalt residue were affected by vacuum saturation more than mixtures contained 4% asphalt residue. The reason for this effect could be due to the relatively large amount of air voids in case of 3.25% asphalt residue content, and consequently the large amount of moisture absorbed by the mixture during vacuum saturation. It was found also that the air cured specimens were affected by vacuum saturation more than oven cured specimens. However, the difference in behavior between dry and vacuum saturated specimens was not large in general.

The instantaneous resilient Poisson's ratio values of vacuum saturated specimens were higher than Poisson's ratio values of the corresponding dry specimens at one-day air curing. At three-day oven curing, however, the opposite was true. The reason for this effect is that one-day air cured specimens were not firm enough so that vacuum saturation softened the mixture and increased the value of Poisson's ratio.

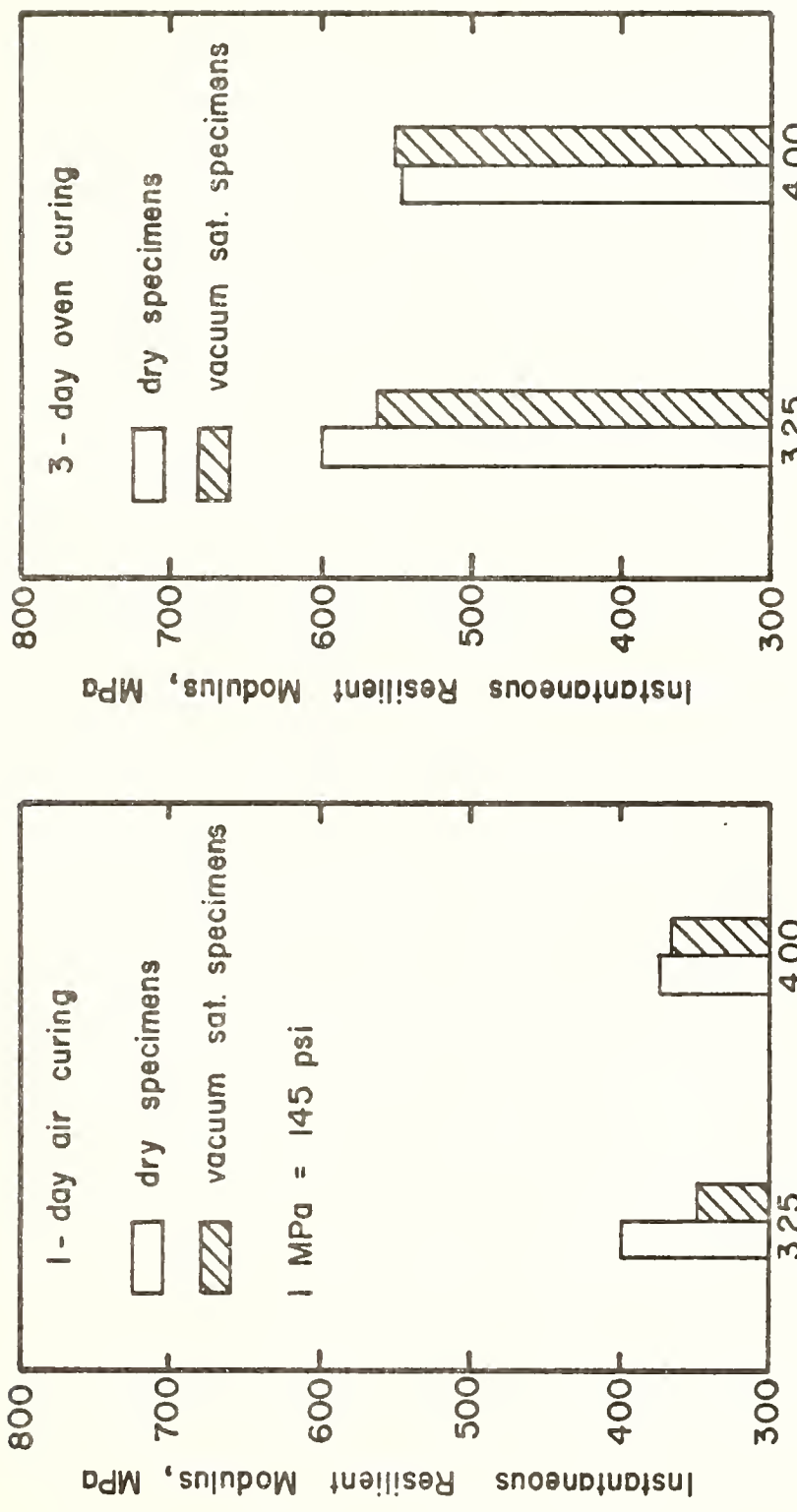


FIGURE 5.19, AVERAGE INSTANTANEOUS RESILIENT MODULUS FOR DRY AND VACUUM SATURATED SPECIMENS FOR DIFFERENT ASPHALT EMULSION CONTENTS AND CURINGS (medium aggregate gradation, 3% W and 24°C (75°F) test temperature)

In general, the resilient characteristics of the asphalt emulsion mixtures evaluated in this study were not severely affected by vacuum saturation. The reason could be due to the use of dense graded mixture which had a small amount of voids and consequently small potential of moisture absorption. The amount of moisture absorbed by the mixture during vacuum saturation did not exceed 2.5% by weight of dry aggregate for any mixture included in the study. The moisture absorption during vacuum saturation took the same trend as the specimens used in the indirect tensile test study. The average values of moisture absorption for the different mixtures are shown in Table 5.5.

Table 5.5 Average Percents of Moisture Absorption During Vacuum Saturation for the Different Asphalt Emulsion Mixtures

Aggregate Type	Sand & Gravel		Limestone	
AE Radius	3.25%	4%	3.25%	4%
1-day air curing	1.705	0.876	1.735	0.880
3-day oven curing	1.660	0.945	1.894	1.369

The moisture absorbed during vacuum saturation by mixtures containing 3.25% AE residue was larger than moisture absorbed by mixtures containing 4% AE residue. Also, oven cured specimens absorbed more moisture during saturation in most cases than air cured specimens. In addi-

tion, limestone mixtures absorbed more moisture than sand and gravel mixtures due to the large amount of voids in the limestone mixtures. The moisture absorption, in general, was related to the amount of air voids in the mixture. The correlation coefficient between percent moisture absorption and percent air voids was 0.80 for the 24 vacuum saturated specimens used in this part of the study.

The percent total liquid after vacuum saturation, was affected by both curing condition and asphalt emulsion content as shown in Table 5.6.

Table 5.6 Average Percents of Total Liquid of Vacuum Saturated Specimens for the Different Asphalt Emulsion Mixtures

Aggregate Type	Sand & Gravel		Limestone	
AE Radius	3.25%	4%	3.25%	4%
1-day air curing	6.397	6.450	6.270	6.417
3-day oven curing	5.437	5.813	5.783	6.285

High values of total liquid were obtained at one-day air curing compared to 3-day oven curing. Also, mixtures containing 4% asphalt residue had higher values of total liquid than mixtures containing 3.25% asphalt residues. In addition, the amount of total liquid for vacuum saturated specimens was larger than the amount of total liquid for the correspond-

ing dry specimens.

The correlation between the amount of total liquid and the M_R value of the mixture was investigated. However, the data were not well correlated for either the dry or the wet conditions because of the large number of factors involved in the study.

5.6 Relationship Between Resilient Modulus Test Results and Indirect Tensile Test Results

The relationship between the resilient modulus test results and the indirect tensile test results was investigated in this section. The asphalt emulsion mixture properties for the similar factor combinations which were considered in both tests were compared. These factors were as follows:

1. Aggregate type; sand and gravel mixture and limestone mixture.
2. Asphalt emulsion residue content; 3.25 and 4% by weight of the dry aggregate.
3. Initial added moisture; 3 and 4.5% by weight of the dry aggregate.
4. Curing; 1-day air curing and 3-day oven curing.
5. Test temperature; 10, 24 and 38°C (50, 75 and 100°F).

One aggregate gradation was considered which was the medium gradation, MG (Figure 3.1). The combinations of 1-day air curing and 38°C (100°F) test temperature together with other factors were not considered because no data were available from the resilient modulus test at these conditions. Therefore, 40 cases representing all other factor combinations were evaluated. For every case, the average values of the three replicates in one test were plotted versus the corresponding average values from the other test.

Regression equations and correlations between the different values were investigated. The indirect tensile test results, such as the indirect tensile strength and stiffness values, were considered as independent variables in the regression equations since they were more reliable than the resilient modulus values. According to these regression analysis, it was assumed that the independent variables had no errors and that the errors in the dependent variable were normally and independently distributed with a zero mean and a constant variance.

The instantaneous resilient modulus values and the corresponding indirect tensile strength values are plotted in Figure 5.20. A correlation coefficient of 0.915 was obtained between the two variables. A linear regression equation was fitted using the available data with an R^2 value of 0.836 as shown below

$$M_R = 301 + 1.35\ \sigma_{IT}$$

where

M_R = Instantaneous resilient modulus, MPa.

σ_{IT} = Indirect tensile strength, kPa.

Meanwhile, the correlation coefficient between the instantaneous resilient modulus values and the corresponding indirect tensile stiffness values was 0.790. The relationship between the two parameters is shown in Figure 5.21. A non-linear regression equation, with an R^2 value of 0.810, was fitted between them for the 40 corresponding cases as shown below

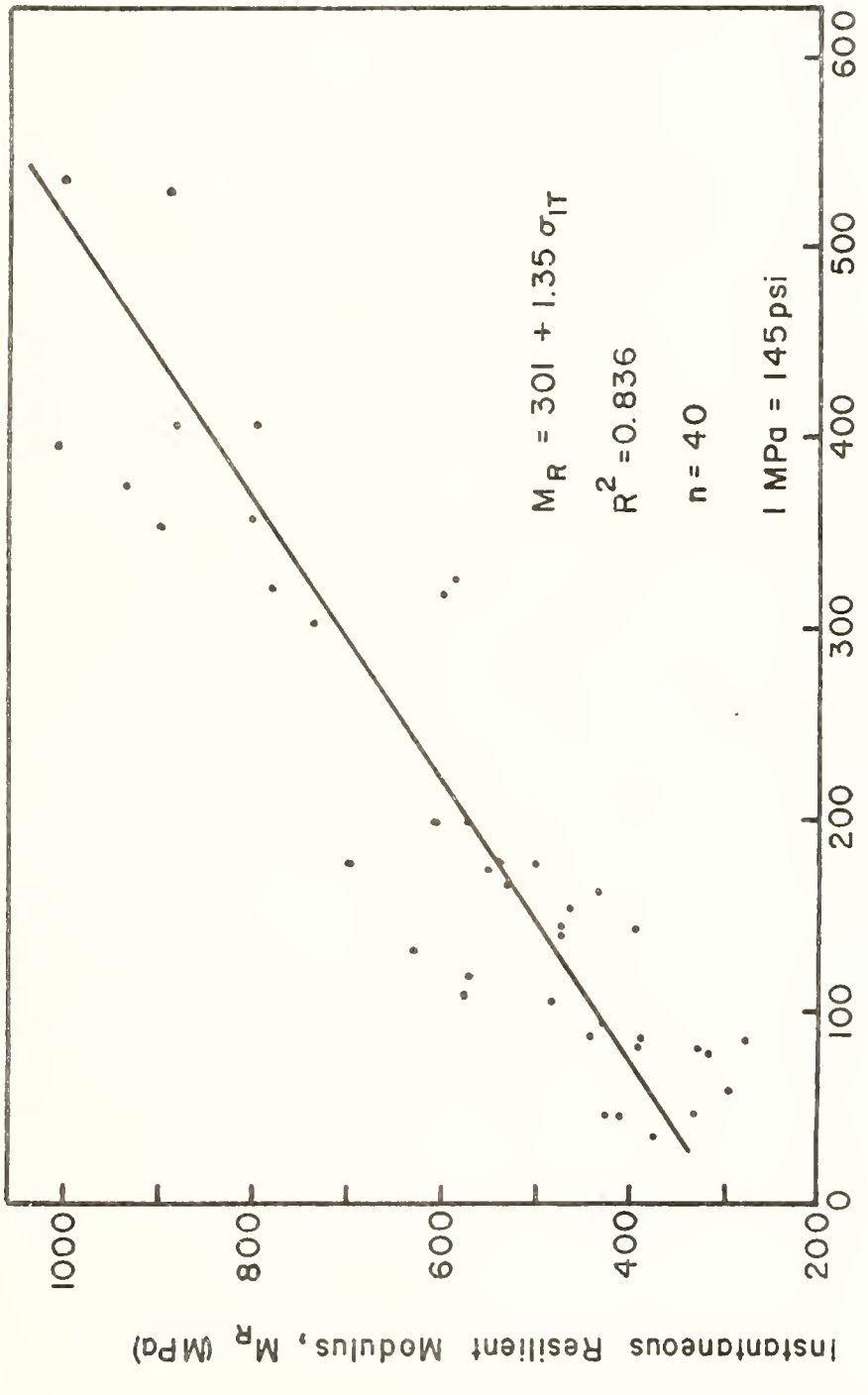


FIGURE 5.20, RELATIONSHIP BETWEEN INSTANTANEOUS RESILIENT MODULUS AND INDIRECT TENSILE STRENGTH

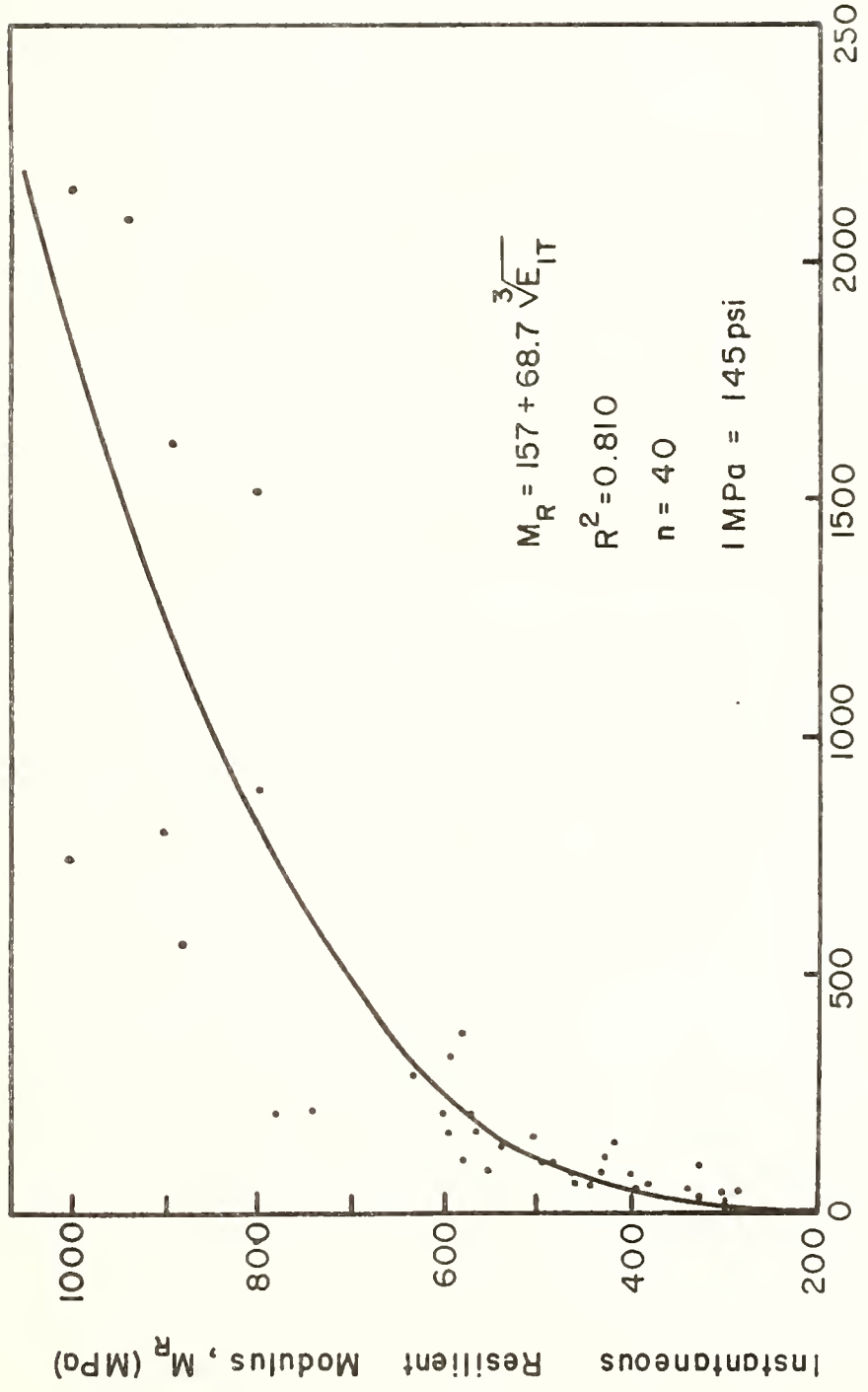


FIGURE 5.21, RELATIONSHIP BETWEEN INSTANTANEOUS RESILIENT MODULUS AND INDIRECT TENSILE STIFFNESS

$$M_R = 157 + 68.7 \sqrt[3]{E_{IT}}$$

where

M_R = Instantaneous resilient modulus, MPa.

E_{IT} = Indirect tensile stiffness, MPa.

It is obvious that there is a good correlation between the instantaneous resilient modulus values and the indirect tensile test results. Since the indirect tensile test is easier to perform and has less variability in results than the resilient modulus test, the previous equations can be used to predict the M_R value from the indirect tensile strength or stiffness values. These regression equations, however, are valid for the SI units only and should be used within or close to the range of values obtained in this study.

5.7 Summary of Resilient Modulus Test Results

The resilient characteristics and other properties of the asphalt emulsion mixes were investigated in this part of the study. The diametral resilient modulus test was performed on mixtures for several mix components and environmental conditions. The different variables which were considered were: two aggregate types and gradations, two asphalt emulsion contents, three initial added moisture contents and three curing conditions. One asphalt emulsion type and grade was used. The test was performed at three different temperatures. A summary of the resilient modulus test results and other properties of the asphalt emulsion mixtures is presented in Table 5.7 and Appendix D. Based on the results obtained in this study, the following conclusions were determined:

1. Test temperature proved to be the most important factor which af-

Table 5.7 Summary of the Resilient Modulus Test Results and Other AEM Properties

Measurements	Range	Important Factors
MR	212-1157 MPa (30.7-167.8 ksi)	T, C, AG
ν	0.1-0.45 (approximately)	T, C, AE, AG, W
CM	2280-2483 kg/m^3 (142.3-154.9 pcf)	AE, GR, AG
γ_w	2275-2457 kg/m^3 (142.0-153.3 pcf)	AE, C, GR, AG
γ_d	2252-2426 kg/m^3 (140.5-151.4 pcf)	AE, GR, AG
%WC	0.25 - 2.24%	C, W, AE
%TL	3.50 - 6.19%	AE, C, W
$\%V_A$	2.18 - 11.12%	AE, C, GR, AG
$\%V_T$	5.57 - 13.81%	AE, GR, AG
%VMA	14.27 - 20.42%	GR, AG

fected the resilient characteristics of the asphalt emulsion mixture. Increasing the test temperature reduced the instantaneous resilient modulus (M_R) values and increased the instantaneous resilient Poisson's ratio values. Reasonable and relatively consistent resilient modulus test results were obtained at low and intermediate temperatures. At 38°C (100°F) test temperature, however, the test was difficult to perform because of the large deformations and the frequent occurrence of cracks.

2. Aggregate type affected the resilient characteristics, unit weights and amount of voids in the mixture. Large M_R values and small instantaneous resilient Poisson's ratio values were obtained using limestone mixtures compared to sand and gravel mixtures. In addition, limestone mixtures provided a larger amount of voids than sand and gravel mixtures.

3. Aggregate gradation affected the unit weights and percent voids in the mixture. Medium graded mixtures provided high unit weights and small percent air voids compared to coarse graded moistures. The interaction of aggregate type and aggregate gradation proved to have a significant effect on the unit weights and amount of voids in the asphalt emulsion mixture.

4. Increasing the asphalt emulsion residue content from 3.25 to 4% by weight of the dry aggregate increased the values of the instantaneous resilient Poisson's Ratio and the unit weight of the mixture. It also increased the amount of retained moisture and the total liquid in the mixture. Both air voids and total voids were de-

creased by increasing the asphalt emulsion content.

5. Curing had a large affect in developing the strength of the asphalt emulsion mixture. Increasing the curing time and/or temperature increased the M_R values and decreased the instantaneous resilient Poisson's ratio values. Curing also decreased the wet unit weight and the retained moisture and increased the air voids in the mixture.

6. The initial added moisture content affected the value of the instantaneous resilient Poisson's ratio. High values of Poisson's ratio were obtained for mixtures contained 3% initial added moisture. The amount of initial added moisture affected the values of retained moisture and total liquid in the mixture for 1-day air curing condition. The effect of initial added moisture content was not significant at 3-day air or oven curings.

7. Vacuum saturation reduced the M_R values of the asphalt emulsion mixtures and changed the instantaneous resilient Poisson's ratio especially for mixtures contained 3.25% asphalt residue and air cured mixtures. However, the effect of vacuum saturation on the resilient characteristics of the mixture was not serious. The amount of moisture absorbed during vacuum saturation did not exceed 2.5% by weight of dry aggregate. Moisture absorption was directly related to the amount of air voids in the mixture.

8. High correlations were obtained between the resilient modulus test results and the indirect tensile test results. Regression equations were fitted between the M_R values and the corresponding indirect tensile strength and stiffness values.

CHAPTER 6

HVEEM TEST

6.1 Introduction

Since the state of Indiana makes use of the Hveem test in the design of asphalt mixtures, it was decided that the asphalt emulsion mixture should be further characterized using the Hveem procedure. The traditional Hveem stability test can not be used for cold mixed asphalt emulsion mixture especially at early ages due to the softness of the mixture. A common procedure used to characterize the asphalt emulsion mixture by means of the Hveem stabilometer is to determine the resistance R-value and a modified Hveen stability at room temperature (35,60). The resistance R-value test has been standardized by ASTM Designation D2844 (AASHTO Designation T190), Resistance R-value and Expansion Pressure of Compacted Soils, which is used for both treated and untreated soils or aggregates. The R-value is used in the design criteria for stabilized base materials. The conventional Hveem stability test is standardized by ASTM Designation D1560 (AASHTO Dsignation T246), Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus.

In this study, both resistance R-value and the modified stability S-value were determined for the asphalt emulsion mixes at room temperature. The relationships between the different mixture components and R and S values were determined for early and long-term curing conditions.

The correlation between R and S values was also investigated.

6.2 Design of Experiment

The objective of the study was to determine the effect of various asphalt emulsion mixture components and curing conditions would have on the Hveem test results. The measured response variables as well as the different independent variables are discussed below.

6.2.1 Response Variables

1. Hveem resistance (R-value), as determined using the Hveem stabilometer at room temperature [22°C (72°F)] (see Equation 6.1).
2. Modified Hveem stability (S-value), as determined also using the Hveem stabilometer at room temperature [22°C (72°F)] (see Equation 6.2).

Both R and S values were determined from the same specimen. The test procedure will be discussed later in this chapter.

6.2.2 Independent Variables (Factors)

The independent variables which were considered in this study are as follows (Table 6.1):

1. Aggregate type, AG; both sand and gravel and crushed limestone were used.
2. Asphalt emulsion residue content, AE; two levels were used which were 3.25 and 4% by weight of the dry aggregate.
3. Curing, C; both one-day air curing at room temperature and three-day oven curing at 49°C (120°F) were investigated. They represented the initial and long-term curings in the field respectively.

TABLE 6.1 , HVEEM TEST VARIABLES

Curing	Aggregate	Sand & Gravel		Limestone	
	% AE Residue	3.25	4.00	3.25	4.00
1-Day Air Curing		X	X	X	X
3-Day Oven Curing		X	X	X	X

Note:

Aggregate gradation: MG

Initial added moisture = 3%

Test Temperature = 22°C (72°F)

One aggregate gradation was used in this study which followed the medium gradation, MG (Figure 3.1). 3% moisture was initially added to all mixtures by weight of the dry aggregate. The tests were conducted at an ambient temperature of 22°C (72°F) whcih was maintained throughout.

6.2.3 Statistical Model

The statistical evaluation which was used in this experiment followed the following model:

$$y_{ijk\ell} = \mu + R_i + \delta_{(i)} + AG_j + R \cdot AG_{ij}$$

$$+ AE_k + \cdots + \omega_{(ijk)}$$

$$+ C_\ell + \cdots + \varepsilon_{(ijk\ell)}$$

where

$y_{ijk\ell}$ = measured response variable (R or S values)

μ = overall mean

R_i = effect of replicate

AG_j = effect of aggregate type

AE_k = effect of asphalt emulsion residue content

C_ℓ = effect of curing

$\delta_{(i)}$ and $\omega_{(ijk)}$ = restrictions on randomization (2)

epsiℓon$_{(ijk\ell)}$ = experimental error

All main effects were fixed except R was random. The subscripts assumed values:

i = 1, 2, 3

$j, k, \ell = 1, 2$

This model followed the split plot design (2). According to this model, three replicates for each factor combination were tested. One replicate (R) for all combinations was performed first. The second replicate was performed next then the third replicate. For each replicate, tests were performed on specimens having a certain curing level (C) before considering other curing levels. Within every curing level, tests were completely randomized for the different aggregate types (AG) and asphalt emulsion contents (AE). All factors and interations were tested versus their interactions with the replicate R. This method of design allows tests for all factors and interactions despite the restrictions on randomization. A level of significance of 5% was used for the different tests. A total of 24 specimens were tested in this part of the study representing all the factors' combinations. A typical ANOVA table of the resistance R-value is presented in Appendix B.

6.3 Experimental Procedure

After the specimens had been cured for the requied amount of time and the unit weight determined as discussed before (Chapter 3), they were tested in the Hveem stabilometer (Figure 6.1). The test followed the standard methods given by ASTM Designation D1560 and D2844 with some modifications (13,35). Two variables were obtained, namely, the Hveem resistance (R-value) and the modified Hveem stability (S-value). According to Tia (60), the value D_2 which is the displacement value used in the calculation of both R and S values (Equations 6.1 and 6.2) does not change at repeated testing. The value of D_2 is a function mainly of the surface texture of the specimen. Thus, both R and S values were ob-

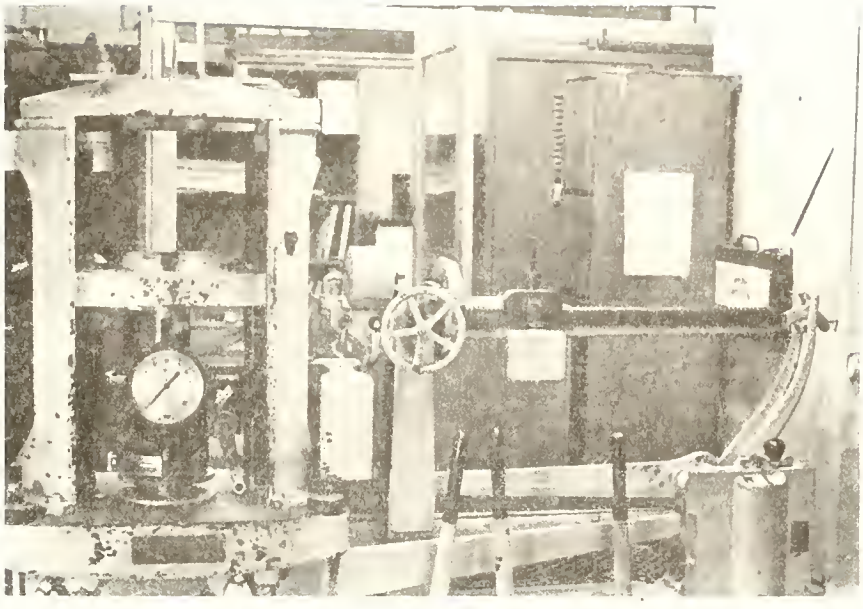


FIGURE 6.1, HVEEM STABILOMETER AND TESTIN MACHINE

tained for the same specimen in one test. The vertical load applied to the specimen was increased up to 22.25 kN (5000 lb.) only and not 26.70 kN (6000 lb.) as specified by ASTM standards in order to reduce the excessive deformation to the specimen. Also, the test was performed at room temperature and not at 60°C (140°F) required by ASTM method. The following is a brief description of the experimental procedures followed in this study.

1. Calibrate the displacement of the stabilometer according to ASTM standards.
2. Transfer the specimen to the stabilometer.
3. Place the follower on top of the specimen and crank the pump to give a horizontal pressure of 34.5 kPa (5 psi).
4. Apply the vertical load with a rate of loading of 1.3 mm (0.05 in.) per minute, and record the stabilometer gauge readings at test loads of 2.22 kN, 4.45 kN and each 4.45 kN thereafter up to a maximum of 22.25 kN (500, 1000, 2000, 3000, 4000 and 5000 lb.). These load values correspond to vertical pressures of 276, 552, 1103, 1655, 2206 and 2758 kPa (40, 80, 160, 240, 320 and 400 psi) respectively.
5. Stop the vertical load and determine the displacement D_2 value according to ASTM standards.

6.4 Analysis of Results

6.4.1 Hveem Resistance (R-Value)

The Hveem resistance (R-value) is an empirical number which measures the deformation of the specimen as a function of the transmitted lateral pressure to that of the applied vertical pressure. It is calculated using the following equation.

$$R = 100 - \frac{100}{\frac{2.5}{D_2}\left[\frac{P_v}{P_h} - 1\right] + 1} \qquad 6.1$$

where

R = Hveem resistance value

P_v = Applied vertical pressure, 1.10 MPa (160 psi)

P_h = Horizontal pressure at P_v = 1.10 MPa (160 psi)

D_2 = Displacement of the stabilometer fluid necessary to increase the horizontal pressure from 34.5 to 689 kPa (5 to 100 psi)

The calculated Resistance R-value was corrected to a specimen height of 64 mm (2.5 in.) according to ASTM standards. The average of the corrected R values determined for the asphalt emulsion mixtures in this study was 84.45 with a maximum of 89.90 and a minimum of 71.87 for all specimens. The lowest R-value obtained for a certain combination of factors as an average of 3 replicate specimens was 76.7. This value was obtained using the sand and gravel mixture with 3.25% asphalt emulsion residue content at one-day air curing. According to the design criteria recommended by Chevron (13), the minimum R-value for dense graded initially cured asphalt emulsion mixtures used for base coarses is 70. Furthermore, the criteria requires a minimum R-value of 78 for final-cured water soaked specimens. Although no water soaking test was performed in this part of the study, the asphalt emulsion mixtures used in this study surpassed the minimum R-value for the initial curing condition.

The ANOVA results indicated that the aggregate type was the most important factor that affected the resistance R-value. Limestone provided a more stable mixture than sand and gravel. The average R-value

for all sand and gravel mixtures in the study was 80.94 as compared to 87.96 for limestone mixtures.

The effect of asphalt emulsion content, aggregate type and curing on the R-value is shown in Figure 6.2. In all cases larger R-values were obtained for limestone mixtures when compared to sand and gravel mixtures for the same curing level and asphalt emulsion content. Meanwhile, for most cases, mixtures containing 3.25% asphalt residue displayd higher R values than mixtures containing 4% asphalt emulsion residue for the same aggregate type and curing level. Also, generally, increasing curing time and temperature increased the R value of the mixtures.

6.4.2 Modified Hveem Stability (S-value)

The Hveem stability (S-value) is a measure of the stability of the mixture. The modified S-value for the asphalt emulsion mixes was determined at room temperature and calculated using the following equation:

$$S = \frac{22.2}{\frac{P_h D_2}{P_v - P_h} + 0.222} \qquad 6.2$$

where

S = modified Hveem stability value

P_v = Applied vertical pressure, 2.76 MPa (400 psi)

P_h = Horizontal pressure at P_v = 2.76 MPa (400 psi)

D_2 = Displacement of the stabilometer fluid necessary to increase the horizontal pressure from 34.5 to 689 kPa (5 to 100 psi)

The calculated S values were corrected to a specimen height of 64 mm (2.5 in.) according to ASTM standards. The corrected S values ob-

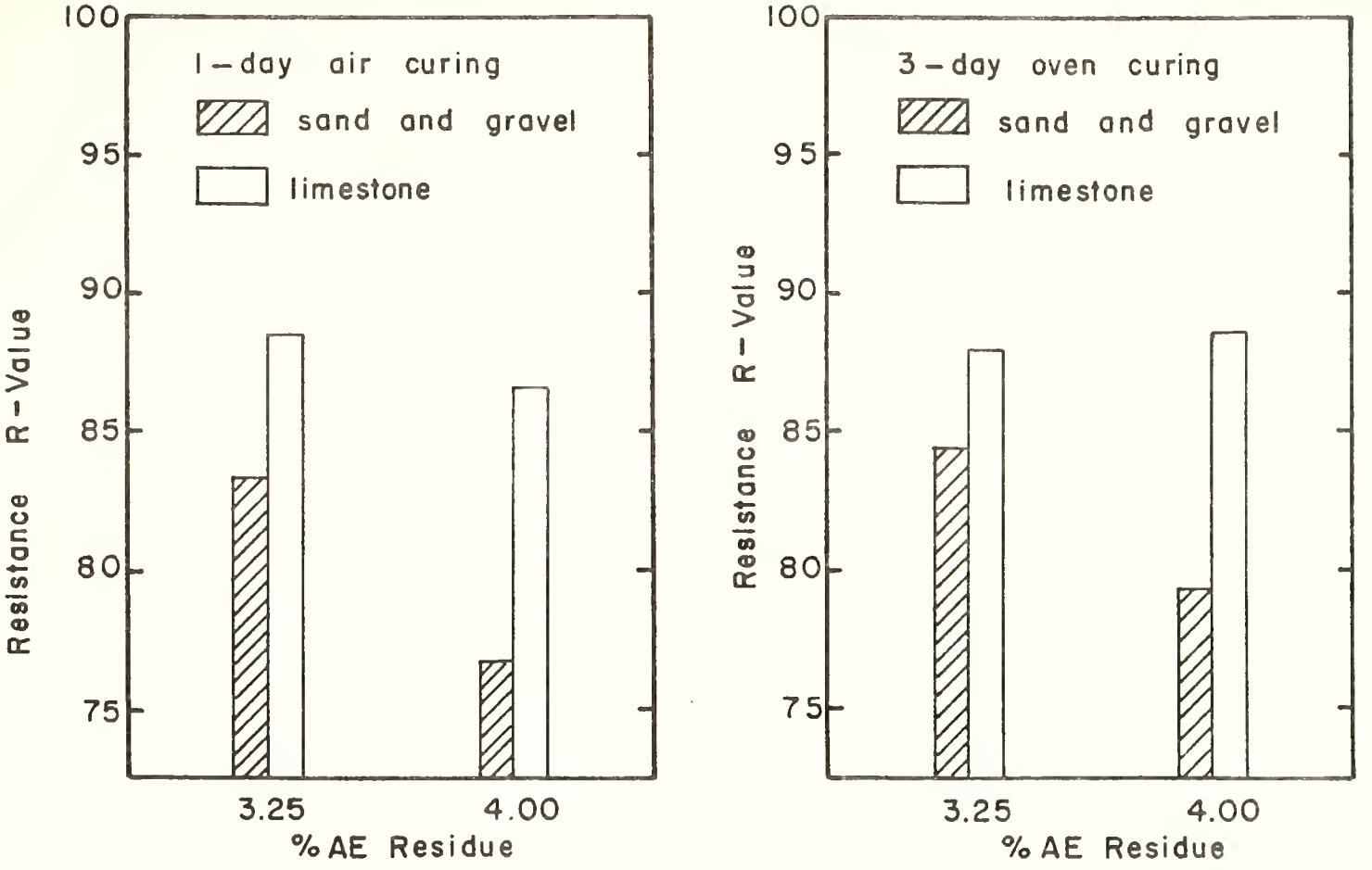


FIGURE 6.2 , EFFECT OF ASPHALT EMULSION CONTENT, AGGREGATE TYPE AND CURING ON THE RESISTANCE R-VALUE
(medium gradation and 3% initial added moisture)

tained for the asphalt emulsion mixtures ranged between 17.45 to 42.00 for all specimens tested in the study with an average of 31.23.

The statistical ANOVA tests showed that the modified S value was largely affected by the type of aggregate. Sand and gravel mixture gave an average S value of 25.47, while limestone mixtures gave an average value of 36.99. The effect of the asphalt emulsion content and curing on the S value was not significant. However, the interaction of the asphalt emulsion content, aggregate type and curing was found to have a significant effect on the value of S. The average S values for the different factor combinations are depicted in Figure 6.3.

In most cases, the different factors had the same effect on R and S values. In addition, R and S values were very well correlated. The correlation coefficient was 0.928 for the 24 cases of R and S values. The relationship between R and S values is shown in Figure 6.4.

A correlation analysis was performed between the Hveem test results and the corresponding results of both the indirect tensile test and the resilient modulus test. In this analysis, the averages of the three replicates in each cell were considered. A correlation coefficient of 0.805 was found between Hveem resistant R-values and the corresponding indirect tensile strength values. Also, it was found that the correlation coefficient between the modified Hveem S-values and the corresponding indirect tensile strength values was 0.781. The Hveem test results and other indirect tensile test and resilient modulus test results were not highly correlated.

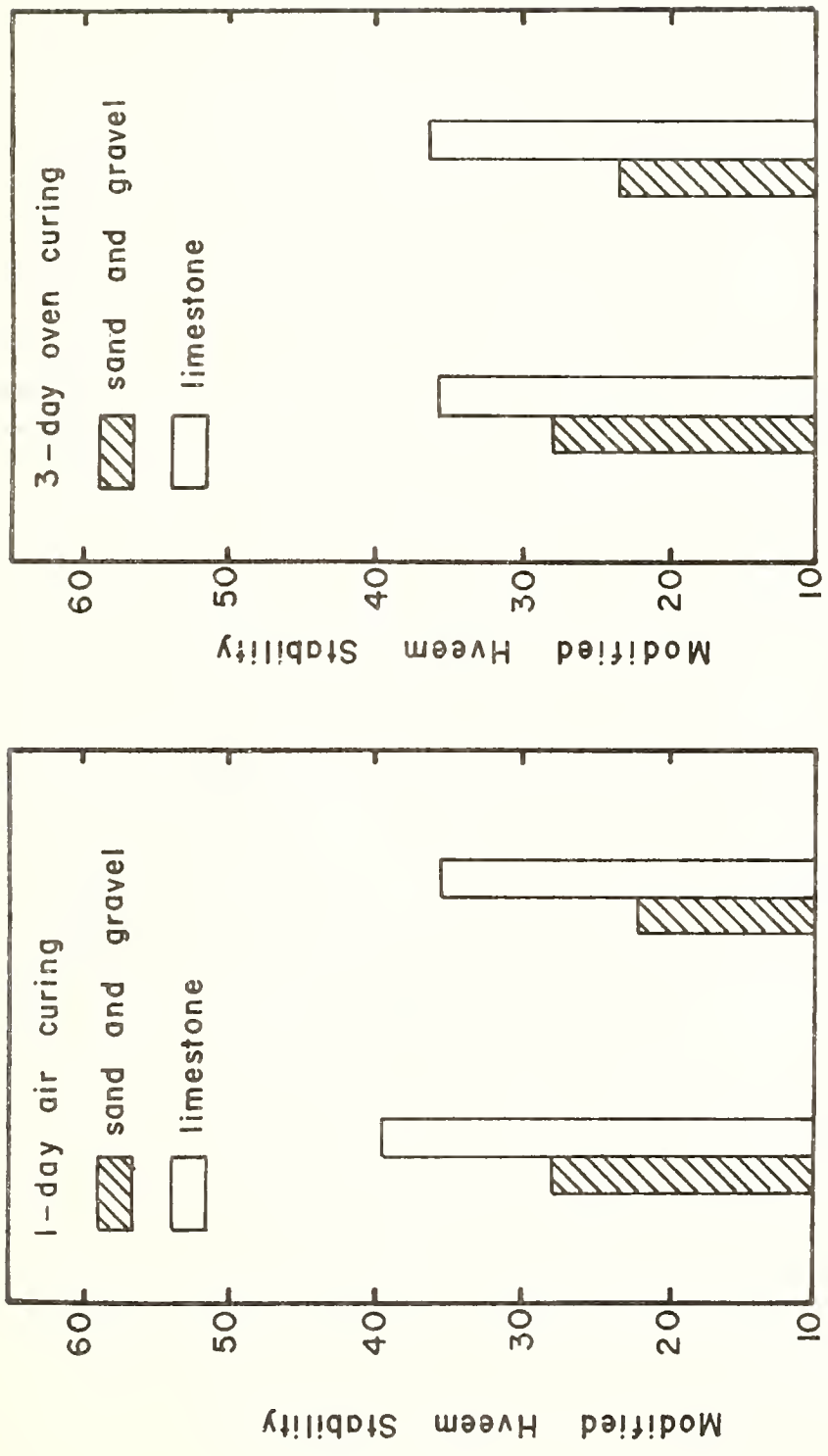


FIGURE 6.3, EFFECT OF ASPHALT EMULSION CONTENT, AGGREGATE TYPE AND CURING ON THE MODIFIED HVEEM STABILITY (medium gradation and 3% initial added moisture)

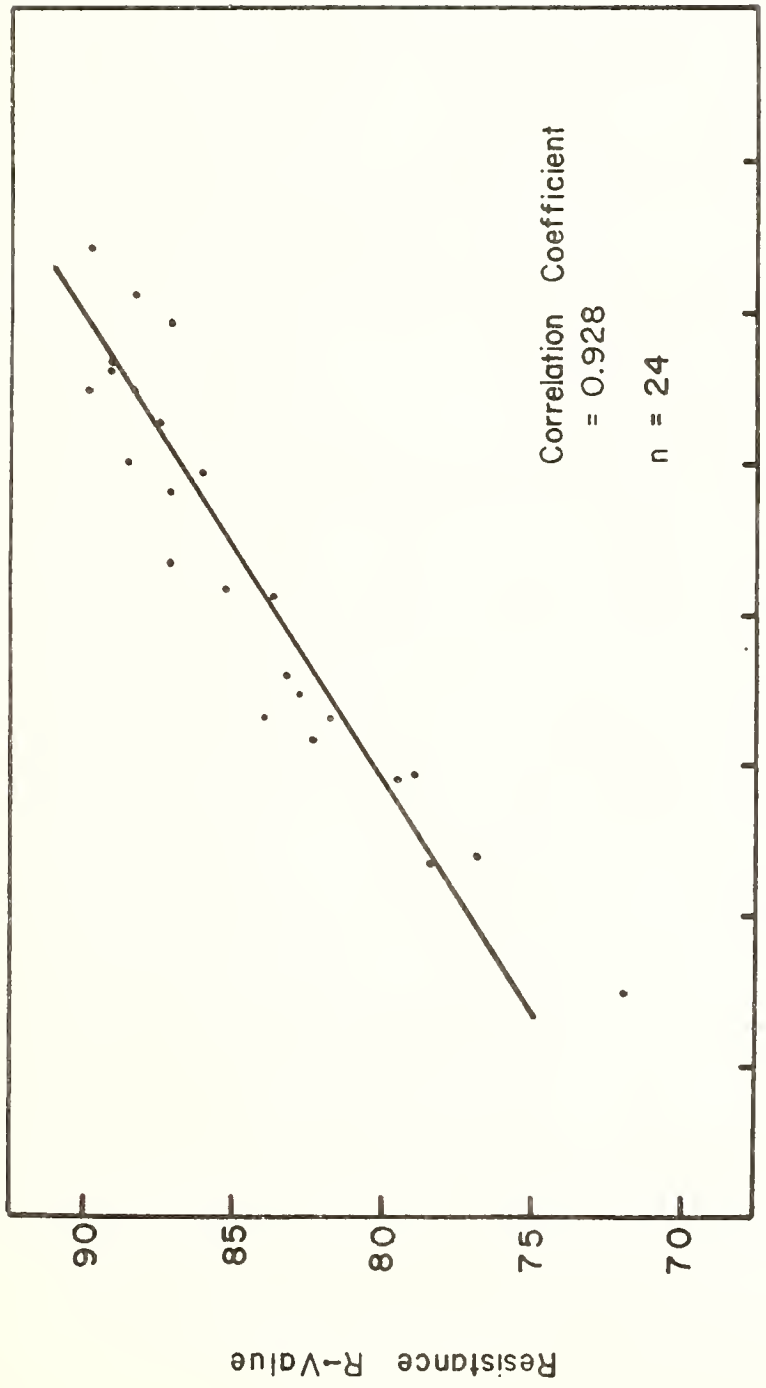


FIGURE 6.4 , RESISTANCE R-VALUE AS A FUNCTION OF THE MODIFIED HVEEM STABILITY (medium gradation and 3% initial added moisture)

6.5 Summary of Hveem Test Results

The resistance R-value and the modified Hveem stability S-value were determined for the asphalt emulsion mixture using the Hveem stabilometer. Two aggregate types, asphalt emulsion contents and curing levels were used in this part of the study. One aggregate gradation was used and 3% initial moisture was added to this mixture. The test was conducted at a room temperature of 22°C (72°F). Both R and S values were determined for the same specimens. A summary of the Hveem test experimental results is shown in Appendix E. The important findings of this study are presented below:

1. Aggregate type was the most important factor that affected both R and S values. Limestone mixtures provided larger R and S values than sand and gravel mixtures for the same levels of other factors.
2. In most cases, increasing the asphalt emulsion content from 3.25 to 4% by weight of the dry aggregate decreased both R and S values slightly. Curing proved to have a small effect on R and S values.
3. R and S values were affected by the different factors in the same way. In addition, R and S values were well correlated. Also, a reasonable correlation was found between the indirect tensile strength and both R and S values.

CHAPTER 7

SUMMARY AND CONCLUSIONS

In this study, a detailed laboratory investigation was performed to characterize the effects of different mix components and environmental conditions on the behavior of cold mixed asphalt emulsion treated bases. One asphalt emulsion (ISHC Designation AE-150) was used throughout the different phases of the study. Two aggregate types and gradations, two asphalt emulsion contents and three initial added moisture contents were evaluated. The asphalt emulsion mixture was characterized at three curing conditions representing the initial, intermediate and long-term curing conditions in the field.

Marshall size specimens were fabricated following the mix preparation procedure developed by Gadallah (27). Specimens were compacted by means of a fixed roller gyratory compaction machine at room temperature. The indirect tensile (split tension) test and the diametral resilient modulus test were performed at three temperatures of 10, 24 and 38°C (50, 75 and 100°F) on both dry and vacuum saturated specimens. The mixture was further characterized using a modification of the Hveem test. The test was conducted at a room temperature of 22°C (72°F) using the Hveem stabilometer.

The indirect tensile properties that were measured were the indirect tensile strength, Poisson's ratio, indirect tensile stiffness, total tensile strain at failure and indirect tensile index. The instan-

taneous resilient modulus and the instantaneous resilient Poisson's ratio were obtained from the resilient modulus test. The vacuum saturated mixture properties were determined using a modification of the water sensitivity test developed by the Asphalt Institute (5). The Hveem apparatus was used to determine the Hveem resistance R-value and a modified Hveem stability S-value. Other asphalt emulsion mixture properties were evaluated such as the unit weight, retained moisture content, total liquid content and voids in the compacted mixture at time of testing. The effects of the different factors considered in the study on the various measured values were investigated. Correlation analyses between the different asphalt emulsion mixture properties were examined. According to the observations and test data the following conclusions were determined.

1. The asphalt emulsion coating on aggregate particles was affected by the shape, surface roughness and mineralogical composition of the aggregate. A better coating was obtained on limestone particles compared to sand and gravel particles.
2. The asphalt emulsion mixture performance was sensitive to temperature. High test temperatures decreased the indirect tensile strength, stiffness and index. The instantaneous resilient modulus was also decreased while the Poisson's ratio values of the mixture were increased.
3. The asphalt emulsion mixture specimens were easy to test at low and intermediate temperatures. At high temperatures, however, hair cracks developed early in the specimens before the test was completed for both indirect tensile test and resilient modulus test.

The resilient modulus test was rather difficult to perform at high temperatures due to the occurrence of these cracks. The assumptions of homogeneous, isotropic and linear elastic materials were not totally met at high temperatures.

4. Limestone mixtures provided better tensile characteristics and larger instantaneous resilient modulus values than sand and gravel mixutures. The unit weight of the mixtures as well as the percent voids in the mixtures were changed according to the change in aggregate type and other factor combinations.

5. Medium graded aggregate provided denser mixtures with higher unit weights and lower air voids than coarse graded mixtures. High indirect tensile strength values were obtained for medium graded mixtures compared to coarse graded mixtures especially for limestone mixtures. However, the effect of aggregate gradation on the resilient characteristics of the asphalt emulsion mixtures were not significant at 5% level of significance.

6. Mixtures containing 3.25% asphalt emulsion residue had higher indirect tensile stiffness and index and lower total tensile strain at failure than mixtures containing 4% asphalt emulsion residue. Meanwhile, increasing the asphalt emulsion content increased the value of the instantaneous resilient Poisson's ratio and the unit weight of the mixture. The amount of retained moisture was increased and the voids were decreased for high asphalt emulsion contents. In general, the optimum amount of asphalt emulsion content depended upon the aggregate type and gradation as well as the ini-

tial added moisture content.

7. Increasing the initial added moisture decreased the indirect tensile strength and increased the instantaneous resilient Poisson's ratio. The effect of the initial added moisture on the amount of retained moisture after curing was apparent at early curing stages. However, longer curing times decreased the effect of initial added moisture. A value of 2-4% initial added moisture by weight of dry aggregate would provide the optimum aggregate coating and mixture workability for the materials and method of preparation used in this study.

8. Curing changed the properties of the asphalt emulsion mixtures. It decreased the amount of moisture in the mixtures, especially the oven curing. High indirect tensile strength and instantaneous resilient modulus values were obtained for oven cured specimens. Curing decreased both Poisson's ratio and the total tensile strain at failure. The wet unit weight of the mixture was decreased and the air voids were increased for long curing times or high curing temperatures.

9. Vacuum saturation had some effect on the tensile properties and the resilient characteristics of the asphalt emulsion mixes. The indirect tensile stiffness and index were reduced by vacuum saturation for oven cured specimens. Also, vacuum saturation reduced the instantaneous resilient modulus values of the mixture, especially air cured specimens with 3.25% asphalt residue content. The effect of vacuum saturation was related to the amount of moisture absorbed into the mixture during vacuum saturation. In general, the affect

of vacuum saturation on the asphalt emulsion mixtures properties was not serious.

10. Moisture absorption during vacuum saturation was directly related to the amount of air voids in the mixture. Moisture absorption was high for oven cured specimens, limestone mixtures and mixes contained 3.25% asphalt emulsion residue. However, the amount of moisture absorbed by the different asphalt emulsion mixtures was relatively small. It did not exceed 2.5% by weight of the dry aggregate in any case.

11. Consistent results were obtained for the indirect tensile test compared to the resilient modulus test. Moreover, the indirect tensile test was easier to perform than the resilient modulus test. Although the MTS electro-hydraulic testing machine was used in the indirect tensile test, the test can be performed using the regular Marshall machine after some modifications.

12. The asphalt emulsion mixtures were suitable to be tested using the Hveem stabilometer at room temperature. Both R and S values obtained from the test were largely affected by aggregate type. Large R and S values were obtained for limestone mixtures as compared to sand and gravel mixtures. Curing and asphalt emulsion content had small effects on R and S values. In addition, R and S values were very well correlated.

13. Reasonable correlations were found between the indirect tensile test, resilient modulus test and Hveem test results. Regression equations were developed between the instantaneous resilient modulus values and both indirect tensile strength and stiffness values.

CHAPTER 8

RECOMMENDATIONS FOR FURTHER RESEARCH

1. The study used one asphalt emulsion type and grade (ISHC Designation AE-150). Other asphalt emulsion types and grades should be investigated to determine the difference between anionic and cationic types of emulsion as well as the different emulsion grades on the asphalt emulsion mixture performance.
2. Correlations between the results obtained in this study and the results obtained using Marshall equipment in previous studies performed by Gadallah (27) and Saxton (49) should be examined.
3. Field data can be obtained to correlate the asphalt emulsion performance in the field with the results of the different tests in the laboratory. Criteria can be developed for asphalt emulsion mixture design.

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APPENDICES

The Appendices are not included in this copy of this report.

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